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ON THE USE OF MENTAL TESTS FOR THE MEASUREMENT OF DISABILITY AFTER HEAD INJURY

WITH A COMPARISON BETWEEN THE RESULTS OF THESE TESTS IN PATIENTS AFTER HEAD INJURY AND PSYCHONEUROTICS

BY

GEOFFREY TOOTH

(RECEIVED 13TH APRIL, 1946)

WHERE knowledge of a medical condition is incomplete, there is a danger that the results of ancillary aids, especially when expressed in numerical terms, may acquire an unwarranted appearance of infallibility. The post-concussional state provides a good example of this tendency, for, while the core of the problem remains obscure, the results of investigations which have only presumptive relationships with the essential condition are liable to be accepted as direct, quantitative indicators of the total disablement. Radiology, psychometry, and electro-encephalography are all open to criticism on this score. For example, though the significance of skull fracture is still uncertain, *x*-ray examination is commonly regarded as essential after head injury. It is perhaps fortunate that only the initiated can interpret an electro-encephalogram tracing; but the result of a psychometric test, usually expressed as a percentage deficit, is apt to stand out, in a case record, as the one fact on which the patient's condition can be assessed. There is no doubt that changes in personality occur after head injury in some cases, and, with them, what appear to be defects of intellectual function, usually at the higher levels. But it is almost certainly incorrect to suppose that intelligence tests measure only high-level intellectual activity; in fact they take a cross sectional sample of conscious mentation, in which affective elements play a most important part. Even in normal persons it is necessary to take account of such factors when a test score is interpreted; their presence in pathological cerebral states introduces, in the opinion of some writers, "an infinite source of error" (Goldstein, 1942a). Nevertheless, mental tests are widely used to measure quantitative intellectual impairment after head injury, and it was to investigate the usefulness of this method of examination that the experiment on which this paper is based was planned.

The basic principles of what is now called differential testing have long been known and were noted by the early workers on aphasia (Hughlings Jackson, 1878) but Babcock (1930) appears to have been the first to apply these principles in the form of mental tests. The theory and technique of the method are fully explained by Brody (1944b), who also gives a review of the literature. It was also observed by Hughlings Jackson (1868) and Henry Head (1920, 1923) that cerebral damage had an apparently specific effect on the ability of some patients to deal with abstract problems. This disability has been more fully explored by the Gestalt psychologists. Goldstein (1942b) regards it as of the greatest importance in understanding the difficulties of the head injury patient, and Weigl (1927), among others, has devised a test to reveal it.

In order to investigate the usefulness of mental tests for the measurement of disability after head injury, one hundred patients who gave a history of a head injury were examined and given a series of tests. Their performance was compared with that of fifty normal persons and fifty psychoneurotics. The last were included because of the similarity between the symptoms of some types of neurotic and some post-concussional patients, and to examine the possibility that neurosis alone might be the cause of the failure in these tests reported by other writers.

Material and Methods

The head injury series was made up of one hundred Naval Officers and ratings who had been admitted to a naval hospital with the history of an injury to the head and a diagnosis of "post-concussional state". These patients were a consecutive series, the only conditions for inclusion being the clear history of one or more head injuries and the patient's ability to co-operate in the tests. In a number of cases the patients were referred to

the writer for a psychiatric opinion because they complained of symptoms for which there appeared to be no adequate physical signs; they were, therefore, far from being a random sample of head injuries, but there is no reason to doubt that they were a representative sample of the post-concussional state. It was not considered justifiable to exclude those who had been sent for examination because they were thought to be showing psychoneurotic symptoms, for it is in the assessment of this large group that the information which might be given by mental tests is most needed.

All these men were serving members of the Royal Navy, in no case were cerebral arteriosclerosis, alcoholism, or any other organic medical condition considered to be a contributary factor in their illness. The type of injury ranged from kicks at football to gunshot wounds. Service regulations ruled out the compensation issues, so common in industrial and road accidents, because any injury received on duty, which includes organized recreation or enemy action, is regarded as attributable unless it is due to misconduct or neglect on the part of the patient. In this series, in no case in which the injury was sustained off duty was there any question of compensation from outside the Service at the time the patient was examined. The series includes five "punchdrunks", three of whom, in addition to their boxing injuries, had suffered blows on the head leading to unconsciousness. No case of simple blast concussion was included, although some patients were undoubtedly exposed to blast in addition to direct trauma at the time of their injury.

Table I records the principal clinical characteristics of the head injury series.

TABLE I

A. Number showing abnormalities in the central nervous system	37
Type of abnormality:	
Focal cerebral palsies	21
Paresis of limbs	9
Post-traumatic epilepsy	4
Post-traumatic diabetes insipidus	2
Post-traumatic Parkinsonism	1
B. Length of post-traumatic amnesia:	
Under 1 hour	36
1 to 24 hours	28
Over 24 hours	26
Unknown	10
C. Duration of symptoms:	
Under 3 months	26
3 to 12 months	32
Over 12 months	42
D. Number with *x*-ray evidence of skull fracture	40
E. Results of E.E.G. examination:	
Abnormal	6
Within normal limits	54
Not examined	40
F. Symptoms:	
Headache	70
Irritability	50
Dizziness	45
Disturbance of memory	61
Intolerance of alcohol	18

Clinical characteristics of the one hundred cases of head injury.

The E.E.G. tracings were interpreted by the same investigator in every case. The percentage of abnormal tracings (10 per cent.), is no higher than that found in a random sample of the general population (Hill, 1944) It will be appreciated from Table I that, both from the nature and duration of the complaints, this was a relatively chronic series of head injuries.

Normal Controls and Psychoneurotics

As controls, fifty convalescent patients were chosen from the surgical wards of the same hospital. Care was taken in their selection to exclude any who showed signs of neurosis, who had had a nervous breakdown or a head injury, or who might be intellectually impaired from some other medical cause. All abdominal conditions other than trauma were excluded because of the possible association with neurosis; infections of the ear, nose, and throat, and diseases of the cardiovascular system were avoided for the same reason. The majority of the members of this group had been admitted to hospital for the treatment of internal derangement of the knee joint, fractures of the limbs, or gunshot wounds of the soft tissues. The purpose of the tests was explained to each man, whose co-operation was voluntary.

The tendency to attach the label "functional" to any patient whose symptoms were not accompanied by adequate physical signs, was well established before the last war, and psychiatrists had to face the fact that a large proportion of the cases referred to them could not be classified under any of the recognized nosological headings. While the justification for sending such patients to psychiatrist is not questioned, it would clearly be incorrect to regard all such patients as neurotics. The Service psychiatrist is called upon to see an amazing assortment of persons in whom the only common factor is a relative unwillingness to do what is expected of them in the Service; the textbook neurotic is a rarity. It would, therefore, be misleading to collect a neurotic control group except by a process of rigorous selection. In this experiment, fifty neurotics were chosen out of two thousand cases seen in a naval psychiatric clinic. Great care was taken to include only those showing such positive signs and symptoms as would qualify them for admission to one of the recognized categories of neurotic disorder. No case was accepted whose symptoms were attributable to the stress of war alone; the majority gave a history of personality disorder of long standing and many had had nervous breakdowns before joining the Navy. The characteristics of this group is given in Table VIII.

Mental Tests

Tests were chosen with a view to investigating, firstly what will be referred to as the Babcock hypothesis, namely that a difference between the scores on tests of early and recent knowledge is a measure of intellectual impairment, and secondly, the hypothesis of Goldstein, which singles out the inability to deal with abstractions as the fundamental failing in organic intellectual disorder. The following tests were used: (1) the Wechsler verbal emergency, consisting of five subtests: comprehension,

similarities, vocabulary, arithmetic, and the repetition of digits forward and reversed; (2) Trist's progressive shapes sorting test; (3) Weigl's colour-form sorting test; (4) Kohs' blocks.

The contracted Wechsler test was chosen because it is well known, has been used for this purpose by other writers (Reynell, 1944), is short and simple to administer, and is standardized for adults; it was given and scored according to the author's instructions (Wechsler, 1941). Although the two sorting tests were designed for the same purpose, both were given in this experiment as it was hoped that they might show interesting differences; Trist's test was given first in every case and, for the sake of simplicity, these tests were scored on a pass or fail basis. Both tests, which are fully described by the authors (Weigl, 1927; Trist, 1943), are designed to discover the subject's ability to distinguish between a figure and its background. They involve the formulation of a concept based on the recognition of similarities of shape or colour, and they test the ability of the subject to exchange this concept for an equally relevant one by the perception of a different set of relationships. It is theoretically probable that these tests examine, in the visual sphere, a similar ability to that tested by the appreciation of verbal similarities. The first ten subtests of the Kohs' blocks test were included because some writers have found them of particular value in the assessment of organic cerebral conditions (Nadel, 1938; Benton and Howell, 1941; Reynell, 1944). They were administered according to the author's instructions (Kohs, 1923) but were scored on time alone. Owing to the abnormal distribution of the scores, possibly due to the fact that only the first ten subtests were used, the distribution had to be normalized before the calculations were performed. In every case the tests were presented in the order above listed. The time taken to administer the whole battery was a half to one hour.

Effect of Age: Statistical Methods

It is generally agreed that intellectual ability, as measured by mental tests, declines progressively with age (Wechsler, 1941a; Murphy, 1929; Pintner, 1929). The fall is said to be gradual up to about the age of thirty-five but slightly accelerated thereafter. It is also known that the type of intellectual impairment found in cerebral deterioration from disease may also be present in normal senility (Brody, 1942). In order to reduce the possible effect of age alone, the age distribution of the normals and the neurotics was adjusted to make these groups comparable with the head injuries in this respect. It will be seen from the tables that the mean age of the three groups is closely similar. The intelligence level, as determined by means of the Wechsler test from weighted scores, shows that the mean intelligence quotient of each group is what might be expected from a random sample of the general population. The standard errors of the differences between the means of the raw scores was calculated for each of the Wechsler subtests and for Kohs' blocks. A P value of 1 : 20 was regarded as significant, and one of 1: 100 as highly significant. As the sorting tests were scored on a pass or fail basis, the results were compared by means of the χ^2 test on four-fold tables; Yates's correction for continuity was used in these calculations.

Preliminary Comparison of the Test Performance of Controls, Head Injuries, and Neurotics

In Table II the test scores of the head injuries group and the neurotic group are compared with those of the normal controls. A significant difference between the mean scores in the various tests is recorded as follows: (+) indicates a difference, which is significant if direction is taken into account, (++) indicates a probability of 1 : 20, and (+++) a probability of 1 : 100 or over. The best measure of discrimination on the sorting tests between the groups compared was found to be given by failure in both of these tests, to which the percentages on the bottom line refer.

TABLE II

	50 controls	100 head injuries	50 neurotics
Age	29·00	−1·05	−0·80
I.Q. Wechsler	103·02	−3·68	−0·72
Vocabulary ..	25·76	−0·36	+1·50
Comprehension	10·14	+0·03	+0·96
Similarities ..	10·96	−1·32+	−0·06
Arithmetic ..	8·32	−0·62	−0·34
Digits ..	11·64	−1·12+++	−1·04++
Kohs' blocks	3·98	−0·08	−0·08
Sorting tests ..	14%	38%+++	32%

Differences of mean scores of head injuries and neurotics from controls.

The figure recorded for the digits subtest is the sum of the number of digits retained forward and reversed. This figure is given throughout, as no difference was found between the number retained forward, as opposed to the number retained on a reversed series, in any group. This table shows that the results in the case of the head injuries group support the Babcock hypothesis, inasmuch as the scores in vocabulary and comprehension, which are said to depend largely on information acquired in early life, are almost the same in the three groups, whereas in the remaining subtests the head injuries did worse than the controls. The difference is highly significant in the case of the digits and sorting tests, and, in the similarities, is significant if the fact that it is in the expected direction is taken into account. That this apparently specific type of differential failure is not peculiar to the head injuries and cannot, therefore, be exclusively determined by organic intellectual impairment, is shown

by the comparison between the scores of the controls and the neurotics. For, although the neurotics do better than the controls in vocabulary and comprehension, they share with the head injuries group a difficulty in the performance of the remaining tests. Their failure is significant in the digits subtest, and just falls short of significance in the sorting tests. Comparison between the scores of the head injuries and the neurotics showed that, apart from the uniformly higher intelligence of the latter, there was no significant difference between the scores on any of the tests.

It seems, therefore, that the head injuries and the neurotics are affected by some factor or factors which may be common to both, and which affects their ability to succeed in certain intellectual exercises. The following sections are concerned with an attempt to isolate this factor.

Analysis of the Head Injury Series According to the Severity of Trauma

The head injury series was divided into groups according to factors which are commonly regarded as indicative of the severity of the original injury, with the object of determining whether any association existed between these facts of the history and clinical examination on the one hand, and the test performances on the other. The principal clinical characteristics of the head injury patients are recorded in Table I. Of these, the following were chosen for analysis: (A) the presence of abnormal physical signs in the C.N.S.; (B) the length of post-traumatic amnesia (P.T.A.); (C) the length of time between injury and examination; (D) the presence of skull fracture, revealed by radiographs. Before the test performances of these groups are compared, their relationships with each other will be examined.

Post-traumatic Amnesia and Abnormal Physical Signs

In assessing the severity of a head injury it is customary to pay particular attention to the duration of disturbance of consciousness, of which the duration of post-traumatic amnesia is a convenient though subjective measure. While many writers have attempted to establish a positive correlation between the duration of unconsciousness and the subsequent disablement (Ritchie Russell, 1932; Symonds, 1932, 1935; Winkelman and Eckel, 1934; Ruesch, 1944; Kremer, 1944), no unanimous conclusion appears to have been reached.

In ninety members of the head injury series it was possible to make an approximate estimate of the length of post-traumatic amnesia by combining the account given by the patient with that of those who attended him during the early stages of his illness. By this means the following groups were separated:

(i) P.T.A.	Under 1 hour	N. 36
(ii) P.T.A.	1 to 24 hours	N. 28
(iii) P.T.A.	Over 24 hours	N. 26

Thirty-seven of the head injury cases showed abnormal physical signs in the central nervous system. Table III shows the relationship between the length of post-traumatic amnesia and the presence of abnormal physical signs.

TABLE III

P.T.A.	C.N.S. abnormality
(i) (Under 1 hour)	6 (17%)
(ii) (1 to 24 hours)	9 (32%)
(iii) (Over 24 hours)	17 (65%)

Association between length of P.T.A. and C.N.S. abnormality.

There is clearly a direct relationship between these factors; for example, the difference between groups (i) and (ii) combined on the one hand, and (iii) on the other, is highly significant ($\chi^2=12{\cdot}43$ $+++$).

Time Between Injury and Examination

As none of the head injury patients had recovered from their illness at the time they were examined, it was not possible to make comparisons based on the total length of their illnesses. But, by calculating the time between the date of injury and the date of examination and testing, some measure of the chronicity of their condition was obtained. When the series was divided into three groups on this basis (see Table I) it was found that no significant association existed between the chronicity and any of the other factors considered in this section. While some association between chronicity and the severity of trauma might have been expected, this negative finding is in line with that of Ritchie Russell (1934), who showed that a long period of unconsciousness was not associated with a long period of disability.

Presence of Skull Fracture

The importance of the presence or absence of a fracture of the skull in the assessment of post-traumatic disablement is a point on which there is still no general agreement, although many writers have expressed unequivocal opinions on the subject. Adolf Meyer (1904) says: " Whether the cranium is fractured or not means relatively little. It would seem, however, that for chances concerning life, a relatively extensive destruction of the skull is rather

more favourable than otherwise." Foster Kennedy (1932) gives *x*-ray evidence of skull fracture first place in a list of absolute criteria of head injury sufficient to produce organic change in the brain. Ritchie Russell (1932) says: "It is generally admitted that the degree of damage to the skull gives no definite indication of the degree of damage to the brain." While Denny Brown (1945), analysing a series of two hundred head injuries, found that the presence of a fracture of the skull was associated with a significant delay in recovery but regarded it, nevertheless, as a relatively unimportant indication of injury to the brain.

Forty of the head injury series were found to have had a skull fracture, which had been confirmed by *x* ray; the relationship between the presence of a fracture and the length of post-traumatic amnesia is shown in Table IV.

TABLE IV

P.T.A.	Skull fracture
(i) (Under 1 hour)	14 (39%)
(ii) (1 to 24 hours)	9 (32%)
(iii) (Over 24 hours)	16 (62%)

Relationship between skull fracture and length of P.T.A.

Comparison between the combined groups (i) and (ii), and (iii) gives a significant result ($\chi^2=3{\cdot}95$ ++), suggesting a positive association between skull fracture and a long period of unconsciousness. A significant association was also found between skull fracture and the presence of abnormal physical signs in the C.N.S., for, of those patients with abnormal physical signs, 65 per cent. had also fractured skulls. This comparison yields a χ^2 of 13·53 +++.

Summarizing this section: analysis of groups formed by dividing the head injury series according to facts of the history and clinical examination probably related to the severity of the original injury, shows that there is a direct association between the length of post-traumatic amnesia, the presence of abnormal physical signs, and fracture of the skull. These findings are interpreted as lending support to the view that both a long period of unconsciousness and a fracture of the skull are indications that the brain has been damaged.

Analysis of the Test Performance of Head Injuries, Grouped According to Facts Associated with the Severity of Trauma

Table V shows the comparison between the results of tests of the head injuries, grouped according to factors associated with the severity of trauma, and the controls. It will be seen from this table that the group giving the most abnormal test picture is that composed of those head injury subjects in whom

TABLE V

	50 controls	37 C.N.S.	36 (i)	28 (ii)	26 (iii)	26 1.	32 2.	42 3.	40 fracture
Age	29·00	+0·16	−2·40	+1·55	−2·75	−2·58	−0·91	−0·21	−2·12
I.Q. Wechsler	103·02	−7·24 ++	+2·07	−1·56	−10·02 ++	−0·02	−5·60	−4·95	−2·24
Vocabulary	25·76	−1·06	+1·32	+0·57	− 1·83	+1·82	−0·23	−1·19	−0·28
Comprehension	10·14	−0·36	+1·55 +++	+0·15	− 1·79	+0·86	−0·42	−0·14	+0·14
Similarities	10·96	−2·58 ++	+0·30	−0·96	− 1·82 ++	+0·31	−1·05	−2·53 +++	−0·96
Arithmetic	8·32	−1·32 ++	+0·04	−0·43	− 1·28 ++	−0·28	−1·04 +	−0·58	−0·34
Digits	11·64	−1·64 +++	−0·67	−0·89	− 1·49 +++	−0·99 +	−1·36 +++	−1·02 +	−0·94 +
Kohs	3·98	−0·20	+0·38	−0·27	− 0·29	−0·10	−0·17	−0·22	+0·12
Sorting tests	14%	54% +++	31%	46% +++	46% +++	35%	41% ++	38% ++	45% +++

Differences of mean scores of head injury subgroups from controls.

C.N.S. = Head injuries showing abnormalities in the C.N.S.

(i), (ii), (iii) = Duration of P.T.A. { 0 to 1 hour. / 1 to 24 hours. / Over 24 hours.

1., 2., 3. = Length of time between injury and examination. { under 3 months. / 3 to 12 months. / over 12 months.

abnormal physical signs were found; their significantly lower I.Q. is due mainly to failure in the similarities, arithmetic, and digits subtests. Although no case of gross aphasia was included in the head injury series, it is possible, as other writers have pointed out (Wechsler, 1941b; Patterson, 1944) that the difficulties experienced by some head injury patients in certain forms of intellectual activity may be due to damage to the speech mechanism. It was shown, in the previous section, that there was a close association between the presence of abnormal physical signs in the C.N.S. and the length of P.T.A. There is, therefore, bound to be some overlap between these groups; in fact, seventeen of the patients with a P.T.A. of over twenty-four hours also showed neurological abnormalities. Columns (i), (ii), and (iii) show that differential failure of the expected kind becomes more marked with increasing length of P.T.A., and suggests that some factor associated with the length of P.T.A. is reducing the capacity to succeed in the tests. These findings are of some practical value, inasmuch as they provide objective evidence in support of the clinical impression that the duration of P.T.A. is a valid criterion in the assessment of disablement after head injury. In columns 1, 2, and 3, the head injuries are grouped according to the length of time between the date of injury and the date of examination. Although the differences are not so striking as in the case of P.T.A., there is a tendency for the more chronic groups to do less well on the tests than those more recently injured. In the skull fracture group, the differences are not significant except in the case of the digits and sorting tests, but the general pattern of differential failure is preserved.

In conclusion, Table V shows that, by means of mental tests, groups of head injuries, selected on the basis of clinical criteria associated with the severity of their injury, can be separated according to their test performance in a manner which agrees closely with that afforded by clinical assessment. This suggests that the ability to succeed in these tests is influenced by some factor associated both with the severity of the injury and with delay in recovery from its effects.

Analysis of Symptoms

Of the various symptoms that make up the post-concussional syndrome some are commonly regarded as more "organic", others as more "psychogenic", but, as Symonds (1942) and Lewis (1942) have pointed out, no good purpose is served by attempting to make what must be a largely artificial distinction on these lines. Nevertheless, if symptoms could be graded by reference to an objective criterion of cerebral damage, it might be of some help in the classification and possibly in the prognosis of head injury cases. At present, the only objective evidence of post-traumatic disablement, apart from gross neurological abnormalities, is the patient's reduced capacity to cope with the ups and downs of life in general and his work in particular. It was hoped that, by comparing the frequency of symptoms with the more objective facts of the history and examination that have been analysed in the previous section, some indication might be obtained as to the value of individual symptoms in predicting the degree of disablement. This method has been used by Ritchie Russell (1932) with interesting results but, possibly because of the relatively large number of more chronic, polysymptomatic patients in the series under review, no significant correlations could be established.

Before recording the separation afforded by test methods, a brief review of the nature of the principal symptoms is given.

Subjective Disturbance of Memory.—This complaint is usually described by the patient as absentmindedness: inability to recall names, faces, telephone numbers, and, in the Services, orders. Many patients with this complaint mentioned that they had to rely on a notebook for facts which they would formerly have retained in memory. The same disability has been reported in some cases following treatment by hypoglycæmic coma or convulsants (Brody, 1944a; Tooth and Blackburn, 1939), and is similar to the failure of recent memory found in Korsakow's syndrome. It is considered by some to be unquestionably organic in origin (Ritchie Russell, 1932; Osnato and Gilberti, 1927), and its occurrence has been noted by Head (1901) in patients suffering from various other physical conditions. There is no doubt, however, that closely similar complaints are also made by neurotics.

Irritability.—Of the more specific disorders of personality following a head injury, irritability is one of the commonest. Introspective patients describe it as their response to the well-meaning efforts of friends and relatives to push them into activity which they formerly enjoyed but, since their injury, have felt unable to face. Half the members of the head injury series made this complaint of their own accord, and it is probable that the number would have been larger if the opinion of friends and relatives had been available. Although rarely found in simple neurosis, irritability is a common accompaniment of many other physical ailments and may well be a structurally determined, primitive response of the organism, which is seeking a safe hiding-place where the demands of society are minimal and where it can readjust itself in peace. This theory, which

was suggested by Head (1901), will be amplified later.

DIZZINESS.—Subdivision of this group by means of physiological tests might have been worth while had the head injury series been larger, but in the circumstances it was not attempted. Thirty-one per cent. of the patients making this complaint also showed neurological abnormalities, suggesting that, in them, this symptom may have had a physical basis.

HEADACHE.—Of all the symptoms that go to make up the post-concussional syndrome, headache is both the commonest and the least specific. Ritchie Russell (1932) found no significant relationship between the severity of the head injury, as estimated by the duration of unconsciousness, and the frequency or severity of headache. Jefferson (1941) expresses a doubt as to the validity of all headache after head injury, and Cairns (1941) regards it as organic but influenced by emotional and psychoneurotic factors. McConnell (1942) found that headache as an isolated symptom in an otherwise normal person after a head injury was usually associated with sub-dural hæmatoma. In only four of the seventy patients who made this complaint was it an isolated symptom, and in none of these was it severe, or associated with physical signs in the central nervous system.

Relationship between Chronicity and the Frequency and Type of Symptom

While there are clinical grounds for suspecting that the more chronic head injury patients present the most numerous complaints, Table VI shows that this is not wholly true. Comparing the frequency of the symptoms of the three groups formed according to the length of time between injury and examination, it will be seen that, though the most chronic group complain of more symptoms than those more recently injured, the differences are significant only in the case of disturbance of memory and irritability.

TABLE VI

Frequency	61	50	45	70
Symptom	Memory	Irritability	Dizziness	Headache
1. Under 3 months	7	6	9	15
2. 3 to 12 months	22	19	15	24
3. Over 12 months	32	25	21	31
Difference between groups 1 and 3 ..	$\chi^2=13{\cdot}99$ +++	$\chi^2=7{\cdot}19$ +++	$\chi^2=0{\cdot}98$	$\chi^2=1{\cdot}24$

Relationship between frequency and type of symptom and length of time between injury and examination.

Although the opinion of the authorities is not unanimous, there is a tendency to regard the complaints of memory disturbance and irritability as more probably determined by physical factors than headache and dizziness. While no evidence in support of this view could be obtained from the material, a significant association between the chronicity of the condition and the complaints of memory disturbance and irritability, shown in Table VI, is interpreted as evidence that the complaints of even the most chronic head injury patients may have a physical basis.

Analysis of the Test Scores of the Head Injury Series Grouped According to Symptoms

TABLE VII

	61 H. I. Memory	39 H. I. Non-Memory	Difference	50 H. I. Irritability	50 H. I. Non-Irritability	Difference
Age	28·65	26·87	+1·78	29·20	26·70	+2·50
I. Q. Wechsler	97·08	102·46	−5·38	97·20	101·16	−3·94
Vocabulary ..	27·18	26·31	+0·87	25·52	25·28	+0·24
Comprehension	9·84	10·69	−0·85	9·60	10·74	−1·14
Similarities ..	8·47	11·38	−2·91 +++	8·56	10·72	−2·16 ++
Arithmetic ..	7·51	8·08	−0·57	7·50	7·84	−0·34
Digits ..	10·36	10·77	−0·41	10·30	10·76	−0·46
Kohs' blocks	3·87	3·95	−0·08	3·92	3·88	+0·04
Sorting tests ..	46%	31%		44%	32%	

Differences of mean scores of head injuries complaining of memory disturbance and irritability from the remainder of the series.

The figures in Table VII show that there is a tendency towards differential failure of the expected kind in both these groups, but only in the similarities subtest is the difference significant. The fact that the patients complaining of disturbance of memory are able to retain and recall a series of digits almost as well as those who did not so complain is of some interest in that it supports the view expressed by Zangwill (1943) that the retention and recall of a series of digits is not a reliable test of memory. Similar comparisons were made in the case of the groups complaining of headache and dizziness, but no significant difference was found between the scores of these patients and the remainder in any of the tests.

Analysis of the Neurotic Series According to Diagnosis, Symptoms, and Severity

Table VIII shows the principal clinical characteristics of the neurotic series.

In Table II, it was shown that there was a close resemblance between the test performance of the head injuries and the neurotics as compared with the controls. In order to determine whether any particular group of neurotics was responsible for this effect, the series was divided as shown in

Table VIII and the test performances were then compared. The scores of the hysterics and the most severely affected neurotics are compared with the controls in Table IX.

TABLE VIII

DIAGNOSIS:	
1. Hysteria	25
(a) "Constitutional" (i.e.) giving a lifelong history of emotional maladjustment with numerous flights into motivated sickness	9
(b) Pseudo-neurological conversion reactions	6
(c) Hyperventilation hysteria	5
(d) Circumscribed amnesic episodes	3
(e) Hysterical fits	2
2. Anxiety neurosis	18
3. Obsessional neurosis	7
SEVERITY OF ILLNESS:	
1. Severe	30
2. Mild	20
SYMPTOMATOLOGY	
1. Memory disturbance	19
2. Headache	23

Clinical characteristics of the fifty neurotics.

This table shows that the hysterics, compared with the controls, give a pattern of differential failure very similar to that given by the head injuries (see Table II). Direct comparison between the hysterics and the head injuries revealed no appreciable difference in any test; although the similarities subtest went some way towards discriminating between the two groups, the difference did not attain the level of significance ($P = 0{\cdot}2$).

TABLE IX

	50 controls	25 hysterics	30 severe neurotics
Age	29·00	−3·40	−0·67
I.Q. Wechsler	103·02	−1·98	−2·02
Vocabulary	25·76	+0·12	+0·64
Comprehension	10·14	+1·02	+0·79
Similarities	10·96	+0·12	−0·96
Arithmetic	8·32	−0·48	−0·39
Digits	11·64	−1·72 +++	−0·94 +
Kohs' blocks	3·98	+0·06	+0·02
Sorting tests	14%	40% ++	37% ++

Differences of mean scores of hysterics and severe neurotics from controls.

If the inability of the neurotics to carry out certain intellectual tasks was due simply to the general emotional disturbance common to all types of neurosis, it might be expected that those of the neurotics who, on clinical grounds, were judged to be most severely affected, would give the most distinctive type of test performance. Comparison with the controls shows that, while this group gives the characteristic pattern of differential failure, the differences are much less than those given by the hysterics alone.

In order to find out to what extent the hysteric group was determining the pattern of performance of the neurotics as a whole, their scores were compared with those of the remainder of the neurotics and the results recorded in Table X.

TABLE X

	25 hysterics	25 non-hysterics	Difference
Age	25·60	30·80	−5·20++
I.Q. Wechsler	101·04	103·56	−2·52
Vocabulary	25·88	27·80	−1·92
Comprehension	11·16	10·92	+0·24
Similarities	11·08	10·72	+0·36
Arithmetic	7·84	8·12	−0·28
Digits	9·92	11·28	−1·36++
Kohs' blocks	4·04	3·76	+0·28
Sorting tests	40%	24%	P=0·4

Comparison of mean scores of hysteric and non-hysteric neurotics.

It will be seen from Table X that the hysterics are a significantly younger group than the remainder of the neurotics. But, while it is possible that this may account for their slightly lower score in the vocabulary subtest, it is most unlikely to have influenced their performance of the digits subtest, in which alone the difference is significant. It would seem, then, that the hysterics are responsible for most of the difference between the full neurotic series and the controls. Similar comparisons were made between the test performances of those neurotics who complained of memory disturbance and headache, both with the remainder of the neurotic series and with the controls; no significant difference was found by this method of subdivision in any of the tests.

Summarizing this section: it has been demonstrated that a selected series of neurotics gives a pattern of differential failure in mental tests similar to that shown by head injury patients, when both are compared with normals. By dividing the neurotics into groups according to the form of neurosis, its severity, and the complaints of the individual members, it is found that those diagnosed "hysteria" give a pattern of abnormal performance

most nearly approaching that of the head injuries. This finding suggests the existence of a common factor in hysteria and the after-effects of a head injury.

Discussion

Differential testing has been used for demonstrating what has been assumed to be organic intellectual impairment in a number of medical conditions, including post-traumatic states. The method is based on the specific inability of patients suffering from these conditions to succeed in certain tests, while their performance of others is unaffected. It is found to hold good when applied to groups of patients after head injury, and it can be assumed that the performance of the group is representative of the individuals of which it is composed. But, with the exception of two tests, the retention and recall of a series of digits and the performance of simple sorting tests, the method does not give sufficient quantitative discrimination between head injuries and normals to be of much practical importance in the assessment of the individual case. Furthermore, in these two tests, a difference of as great a magnitude was found between the normal controls on the one hand, and a series of neurotic patients in whom no organic condition was known to exist on the other. The Wechsler, vocabulary, and comprehension tests appear to be almost equally efficient measures of ingrained knowledge, in so far as they are done equally well by every group examined. The digits subtest and the sorting tests discriminate to some extent between the various clinical groups, but, as the differences between normals and head injuries and normals and neurotics are so similar, these tests would seem to be of only limited value in the assessment of head injuries. It is possible that the discriminative function of the sorting tests could be improved by taking qualitative differences into account in scoring.

The similarities, and, to a lesser extent, the arithmetic subtest, are the only ones in which the poor performance of the head injuries is not matched by the neurotics. Of the two, the similarities would seem the more worth while for further investigation and development, as it is difficult to believe that even simple arithmetical ability is not, to an appreciable extent, influenced by practice and education. The modified Kohs' blocks test gave no significant difference between any of the groups examined but, although it is outside the scope of this investigation, most interesting qualitative differences of performance were found between various members of all the groups in this test, and it might well be worth while devising methods for recording and classifying these.

Conclusions

The association between test performance and the facts of clinical observation makes it probable that the tests are measuring some factor or group of factors unfavourable for recovery after head injury, but beyond this the interpretation of the results must be mainly speculative. As most of the tests were verbal, it is possible that minor degrees of aphasia may have accounted for some of the failures among the head injury cases, but this would hardly explain all the findings. The nature of the disorder of intellectual function responsible for the distinctive test scores can only be conjectured. As the same pattern of performance is shown both by the neurotics and the head injuries, the common factor can hardly be " organic impairment " in the sense in which this term is used by other writers describing similar findings in general paralysis, cerebral arteriosclerosis, and such like irreversible, deteriorating states. It is, of course, possible that the specific performance of the head injuries was due to organic impairment and that of the neurotics to some unknown factor associated with neurosis but not necessarily with head injury. This explanation cannot be refuted on the data presented in the investigation, but, if it were true, it would raise a doubt as to the value of differential testing for any purpose, for it is virtually impossible to exclude the existence of latent neurosis in anyone; moreover it is well known that tests and examinations are likely to bring out neurotic propensities in otherwise normal persons. Affective disturbances are commonly accompanied by preoccupation and inhibition in the intellectual sphere, and might well influence the performance of tests; but, if this were the explanation of the similarity between the test pattern of the two series, it is surprising that the hysterics, who of all neurotics show the least affective involvement, should give a picture most nearly matching that of the head injuries cases.

An hypothesis to fit the facts presented would need to take account of this similarity between some head injuries and some hysterics. It will be generally agreed that hysteric symptoms are not uncommon after head injury, but, if the specific features of the test performance of the head injuries is attributable to cerebral damage, it is difficult to account for similar findings among hysterics without invoking somewhat speculative theories. There is, however, one outstanding work which links hysteria with organic disease and lends weight to the hypothesis that a type of hysteria may be determined by purely physical factors. In his Goulstonian Lecture of 1901, on " Certain Mental Changes that Accompany Visceral Disease ", Henry Head (1901) describes a

series of patients who, during the course of physical illnesses, showed mental changes. He particularly mentions unaccountable mood swings, often accompanied by paranoid trends, hallucinations, and disturbances of recent memory. He attributes these manifestations to the effects of referred visceral pain and, in his conclusion, excuses himself for indulging in "a fantastic speculation" which amounts to the view that, in certain circumstances, the human organism tends to revert to a primitive type of reaction to illness, and that, when this tendency comes into conflict with the environment, the reaction has all the characteristics of hysteria. The recent experimental studies of Campbell and Parsons (1944) go some way to support this hypothesis. By intracranial injection these workers were able to produce referred pain in normal subjects, whose descriptions of their sensations were closely similar to those of post-concussional patients.

The occurrence of neurotic disturbances, during or after physical illness, is sometimes attributed to the release of such propensities latent in the personality. This explanation would be difficult to controvert, but it fails to account for the not uncommon cases of post-traumatic neurosis in previously stable personalities. It also begs the question of causation. It seems possible that the apparently specific characteristics of the performance of the head injury cases and the hysterics was due to the action of the same primitive mechanism described by Head, activated, in the case of the head injury group, by referred pain from lesions within the cranial cavity. In conclusion, it is suggested that the findings of this investigation can best be interpreted as revealing by mental tests the existence of a type of functional disturbance having the clinical characteristics of hysteria, but organic in origin, and possibly due to referred pain from as yet unidentified changes within the cranium after head injury.

Summary

The method of differential testing, which has been found useful for assessing intellectual deterioration in some organic cerebral conditions, is also widely used for the same purpose in cases of head injury. Differences of performance are interpreted as evidence of organic intellectual impairment, but the absence of objective criteria of damage to the brain in the average post-concussional case makes it difficult to validate such an assumption.

A consecutive series of closed head injuries was compared, by means of a battery of mental tests, with a series of normal people, and a selected series of neurotics. It was found that the pattern of performance of the head injuries was of the expected kind, and that those judged to be most severely injured on clinical grounds gave the most specific type of test pattern. This is interpreted as evidence that the method is testing some factor associated with failure to recover after a head injury.

The investigation lends support to the use of differential testing for analysing the nature of intellectual impairment but, while group differences are clear enough, the deviation of individuals may be so slight or so variable that the method is of limited value in the assessment of the individual case.

As the neurotic subjects showed a pattern of differential failure similar to the head injuries patients, it would seem unjustifiable to conclude that this differential failure is peculiar to organic impairment. The test results of those neurotic subjects diagnosed as "hysteria" most nearly matched the results given by the head injuries patients.

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ÉTAT MARBRÉ OF THE CORPUS STRIATUM FOLLOWING BIRTH INJURY

BY

R. M. NORMAN

From the Burden Mental Research Department, Stoke Park Colony, Bristol

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THE presence of myelinated fibres in aggregations of a density abnormal for that particular region of the nervous system constitutes état marbré. In the cerebral cortex of the adult such localized areas of hypermyelination may occur as an incidental feature of the pathology of cardiovascular disease or of carbon monoxide poisoning. Etat marbré of the corpus striatum, however, appears to be a phenomenon of infancy or, rarely, of early childhood, and its pathogenesis is still a matter of controversy, it being claimed on the one hand that the condition is a prenatal anomaly of growth, on the other that birth injury is the probable causative factor.

There are several lines of evidence giving support to the latter view. First, in a high proportion of the cases in which details of the birth and neonatal period are recorded there is found a history of prolonged or abnormal labour, or of severe asphyxia with difficulty in resuscitating the infant, or of the baby's weakness in early life associated perhaps with epileptic attacks (Meyer and Cook, 1936; Byers, 1942). Attempts to explain these events as the consequences of pre-existing malformation are hardly convincing. Secondly, as was shown by Schwartz (1924; 1926), the bleedings and softenings of fatal birth injury favour a periventricular distribution, the caudate nucleus and thalamus being sites of predilection, these central lesions following stasis in or rupture of the terminal tributaries of the great vein of Galen. This vessel is liable to damage or occlusion during birth by reason of its mode of termination in the straight sinus (Holland, 1920; Clark, 1940). Yagi (1930) has demonstrated that the elastic fibres in the wall of this vein are feebly developed even in fœtuses of seven months, a fact of significance in accounting for the well-known susceptibility of premature infants to birth injury. Furthermore, the experimental work of Schlesinger (1939) showed that sudden occlusion of one small vein of Galen leads to hæmorrhage into the caudate nucleus of the same side. While it cannot be denied that necrotizing lesions of the basal ganglia may follow congestion or stasis in the Galenic venous system during parturition, it is not generally admitted that état marbré is a common sequela of such a process. The probability of such an assumption being correct is considerably increased by the findings in a case reported by Pfeiffer (1939) who described gross bilateral cavitation of the putamina with état marbré in the surrounding tissue. Moreover, in a case of undoubted birth injury recently published by myself (Norman, 1944) marbling of the caudate nucleus was associated with a small adjoining area of anæmic necrosis. Finally, état marbré of the corpus striatum is often combined with lesions of the cerebral cortex which themselves are highly characteristic late neuropathological sequelæ of birth trauma (Benda, 1945). Such, for example, are the hypermyelinated ulegyria or atrophic sclerosis overlying small foci of subcortical softening found with especial frequency in the parieto-occipital areas, and the more massive cerebral softenings represented by large cavities or the diffuse multiloculated type of polyporencephaly described by Juba (1937).

Although the evidence outlined above seems to establish a causal relationship between état marbré and birth injury, this view has been rejected by Alexander (1942), who reaffirmed the original opinion expressed by the Vogts (1920) that the condition is a prenatal malformation, genetically determined. He has claimed that the abnormal myelinated fibre bundles and networks of the putamen are aberrant offshoots of the fronto-pontine tract, and has denied the reality of the coincident gliosis and nerve cell loss first observed by Scholz

(1924) and since confirmed by several other writers on the subject. In view of this conflict of opinion I have thought it profitable to describe the following three new examples of striatal état marbré. These cases support the thesis that the condition commonly results from vascular lesions sustained during birth, and also illustrate additional pathological features of interest to the student of mental deficiency.

Material

Case 1

B. V., a male, was admitted to Stoke Park Colony when 10 years old and died aged 25 years.

History Before Admission.—The mother, an intelligent woman, gave a good account of the circumstances of the birth and early life of the patient. She was in very good health throughout the pregnancy but had no medical antenatal care. It was her first child and she was in her thirty-ninth year. Labour lasted about fifteen hours and " as the labour pains did not increase the doctor gave me chloroform and brought the baby." The infant weighed nearly 10 lb. at birth and was " bluey purple " when the mother first saw him. The doctor in attendance was able to recall the case, for it was the only midwifery he had done since qualification six years previously. He confirmed that the baby was very blue and he " had to work hard for twenty minutes to get it to breathe." Apart from the asphyxia he did not think the case presented any difficulties. There was no history of jaundice in infancy. At the age of 6 months the baby was " quite intelligent looking and laughed and noticed us." He was not breast fed but artificial feeding was satisfactory. There was delay in his ability to sit up without support and as time passed it was noticed that he " never seemed to have control over his arms when he tried to feed himself." His father spent much time trying to teach him to walk, but the child never managed more than a few steps before falling down. He was able to learn the alphabet, and could count and spell short words.

Family History.—There is no history of mental deficiency, epilepsy, paralysis, or stillbirths on either side of the family. There are two other children of the marriage, and they are mentally and physically normal save that the younger has valvular disease of the heart, discovered for the first time when she went to school.

Examination After Admission.—He was a diplegic imbecile with no educational attainments. A neurological examination made when the patient was 21 years old gave the following information. The cranial nerves were normal and there was no nystagmus. He was unable to stand or sit up. Muscle tone was markedly increased in arms and legs, the arms being held in the position of internal rotation with flexed wrists. The knees were contracted and flexed and the legs could not be extended beyond an angle of about 150°. Equinus deformity of both feet was present. Athetosis was severe in the face and arms, and both arms showed a marked rebound phenomenon. Leg movements were handicapped by considerable synergic spasm which affected especially the left side. The tendon reflexes were equal on both sides of the body, the knee jerks being exaggerated and obtainable by striking the whole length of the leg. Both plantar reflexes were extensor in type, and Oppenheim's sign was also present bilaterally. Satisfactory sensory tests could not be carried out, but a marked failure in the ability to localize stimuli was noted. There was severe dysarthria. Measurements of the length and circumference of forearm, arm, thigh, and leg showed no asymmetry. Sphincter control was normal. There was no epilepsy. Subsequently examinations showed little change in the general condition apart from variation in the knee jerks, which were on two separate occasions reported as normal, and also a variable plantar response in the right foot, which was flexor at one examination.

Death occurred at the age of 25 from bronchopneumonia.

Pathology of the Central Nervous System

Macroscopic Examination of the Brain.—The brain weighed 1378 g. of which the cerebellum and attached brain stem accounted for 205 g. The convolutional pattern was normal. Coronal section revealed état marbré in both putamina.

Microscopic Examination.—Blocks of tissue were taken from representative areas of the cerebral cortex and basal ganglia of both sides, from cerebellum, brain stem, and cervical spinal cord. Sections were stained by standard methods for nerve cells, neuroglia, axis cylinders, and myelin.

Putamina.—The myelin stain confirmed the naked-eye impression of état marbré, densely myelinated fibres in the form of interlacing strands occupying mainly the dorsal three-fourths of the caudal portions of both putamina (Fig. 1). On the right side, more anteriorly, these abnormal bundles appeared as a narrow laterally placed fasciculus (Fig. 2). The normal darkly staining and compact fibre bundles of the putamen were intact and showed up clearly even in areas involved in the more diffuse hypermyelination of the marbled state. In sections stained by the method of Holzer for fibrillary neuroglia a dense network of gliosis was demonstrated in the areas of marbling, a rough correspondence as regards intensity being noted between adjacent sections stained for myelin and glia respectively (Figs. 3, 5, 6). Gliosis was more marked around the blood vessels, and shrinkage of the tissue had caused considerable dilatation of the perivascular spaces. A mild fibrillary gliosis was also present in the normal myelinated fibre bundles of the putamen traversing the areas affected by état

marbré (Fig. 6). A conspicuous loss of nerve cells had occurred in the regions showing état marbré, although the larger nerve cells sometimes survived in otherwise devastated areas (Fig. 4). Bielschowsky staining showed numerous axis cylinders of fine calibre occupying these affected areas.

Thalami.—Sections stained by cresyl violet revealed patchy and sometimes extensive areas of nerve cell loss, especially in the lateral nuclei. Such foci were characterized by an increase in glial nuclei, and often by small groups of "calcified" nerve cells (Figs. 7, 10). Holzer staining showed widespread gliosis, sometimes reticulate in pattern (Fig. 9), and in places of extreme density (Fig. 8). In myelin preparations an abnormal density of fibres was seen in parts of the medial and lateral nuclei, an effect enhanced by an occasional patchy poverty of fibres in adjacent areas (Fig. 2). In the nucleus of the left thalamus there was found an area of severe nerve cell loss and gliosis, associated with a conspicuous hypermyelinated plaque of quadrangular shape.

Other Parts of the Brain.—An abnormal gliosis, unassociated with nerve cell or myelin changes, was present around the aqueduct, beneath the floor of the fourth ventricle, and also in the central raphé of the dorsal pons. Elsewhere in brain and cerebellum no pathological features of note were discovered. In particular it may be remarked that the caudate nuclei showed no état marbré, that the pigmentation of globus pallidus and substantia nigra was normal, and that the myelinated fibres of the fronto-pontine and pyramidal tracts were intact.

Case 2

C. G., a female, was admitted to Stoke Park Colony when 8 years 4 months old, and died aged 13 years 9 months.

History Before Admission.—The mother, a healthy farmer's wife, gave a good account of the birth and early life of the patient. The pregnancy was uneventful. It was her first confinement and the baby was full term. Labour started at 6 a.m., and at 12 noon that day the family doctor delivered the infant by forceps. There was some difficulty in getting the infant to breathe, and she was held upside down and smacked. Breast feeding was started, but for the first week or two the child was too feeble to suck properly. The mother noticed when the child was about 8 months old that she "was holding her left hand closed most of the time and was not using it with the other one", also that the left leg appeared to be weak when she started to crawl. At the age of 10 months convulsions were observed. At first "they were more like holding her breath for a few seconds, then gradually became worse as she grew older, occurring two or three times a day." During the fits the left arm and leg became stiff. When the patient was 18 months old daily massage and electrical treatment were instituted, and she began to learn to walk. The arm and hand were useless, however, and she never learned to talk.

Family History.—Father, mother, and grandparents were normal physically and mentally. The patient has a young sister who is also normal.

Examination After Admission.—At the age of 8 years the child was found to be an idiot with severe epilepsy, speechless, noisy, and excitable. She was incapable of performing even the simplest tests of the Merrill-Palmer Scale. Her weight and standing stature were normal, but she was small-headed. The blood Wassermann reaction was negative. A neurological examination at the age of 11 years gave the following information. The left arm and leg were stunted (2 inches and 1 inch shortening respectively). Both hands and feet were cold and blue, the left foot being the more affected. The patient was able to rise from the recumbent position with difficulty and could walk quite well with an obvious hemiplegic limp. The left arm was quite helpless, wrist drop was present, but there was no spasticity and no contractures. There was slight contracture of the left Achilles' tendon, but no evidence of increased muscle tone was found on passive movement of the limb. The left knee jerk was exaggerated, and was obtainable by striking the inner side of the left leg over a wide area. The right knee-jerk was also somewhat brisker than normal. The left plantar reflex was doubtfully extensor, with marked fanning of the toes. The abdominal reflexes were present. The cranial nerves and pupillary reactions were normal. There was no athetosis.

During the last year of her life the patient became feebler, and finally was scarcely able to walk without assistance. Muscle tone became more obviously spastic in the left limbs, and the left plantar reflex was definitely extensor in type. The epileptic fits, never properly controlled by sedatives, had recurred with greater frequency and severity and death from status epilepticus occurred in her fourteenth year.

Pathology of the Central Nervous System

Macroscopic Examination of the Brain.—The brain weighed 850 g., of which cerebellum and pons accounted for 142 g. A large cystic cavity was present in the right cerebral hemisphere, the greater part of the third frontal and superior temporal, and the lower portion of the central gyri having been destroyed. The adjacent parietal convolutions showed marked distortion of pattern and felt sclerotic to the touch. The outer wall of the cyst was composed of a smooth membrane which followed the main convex contour of the hemisphere. Coronal section of the brain (Fig. 11) showed that the cavitation extended deeply into the white substance, being separated by a narrow boundary from a somewhat dilated lateral ventricle. The cortex of the insula had been destroyed. Fine trabeculæ

filled the interior of the cavity. The right hemisphere was about 2 cm. shorter than the left at its occipital extremity. The cerebellum showed slight contralateral atrophy.

Microscopic Examination

Cerebral Cortex.—The thin external wall of the cavity in the right hemisphere was shown on section to consist of a gliotic membrane derived apparently from compressed and atrophied white matter and distinct from its leptomeningeal coverings. Small islands of sclerosed grey matter, sometimes containing a few nerve cells, were present on the surface of this membranous wall (Fig. 13). In the parietal cortex adjoining the cavity extensive sclerotic hypermyelinated ulegyria was present, as illustrated in Figs. 15 and 16. Abnormal myelinated fibres, in the form of plaques, whorls, or reticulated strands, occurred at the edges of areas of total atrophy and heavy glial scarring, a cluster of bizarre microgyric convolutions often sprouting from a common stem of non-myelinated, densely gliotic tissue. The outer surface of such gyri were frequently mammillated, presenting the appearance of "granular atrophy", and on section they showed islands of nerve cells separated by a heavy network of fibrillary neuroglia (Fig. 14). The small distorted convolutions sometimes gave the impression of having adhered and fused at points of contact with one another (Fig. 16). The left side of the brain appeared intact, and neither cornu ammonis showed pathological change.

Basal Ganglia.—Well marked état marbré was present in the right caudate nucleus and in the dorsal quarter of the right putamen (Fig. 12). Gliosis could not be demonstrated except in the putamen, where, after prolonged search of phosphotungstic acid hæmatoxylin preparations under the oil immersion lens, a few fibrils were seen in an area of état marbré In the outer segment of the anterior part of the right globus pallidus, two small foci characterized by dense gliosis and absence of myelin were visible by the naked eye. Microscopic examination revealed masses of "calcified" débris with occasional "calcified" nerve cells in these situations (Fig. 17). No conspicuous increase in Hallervorden-Spatz pigment was seen. The right thalamus was shrunken and showed marked retrograde degeneration of nerve cells. The basal ganglia of the left side appeared to be normal.

Other Parts of the Brain.—In the medulla the right pyramidal tract was very small, but contained thinly distributed myelinated fibres. The left pyramidal tract at this level was of fully normal adult size and appeared somewhat hypertrophied compared with those from other defective brains with which comparison was made. In the cerebellum the cortex and white matter appeared normal, no microscopic differences between the two halves of the cerebellum being observed apart from a slight hypoplasia of the folia of the left hemisphere. The cells of the left dentate nucleus were smaller and often stained less deeply than those of the right.

Case 3

L. W., a female, was admitted to Stoke Park Colony when 9 years 10 months old, and died aged 18 years 7 months.

History Before Admission.—Information as to the patient's early life was scanty since the mother had died from tuberculosis before the child was sent to the Colony, and the father, an unemployed collier, was unable to recall many details. The patient was one of twins and was born at home before the arrival of an ambulance to take the mother to hospital. When in her third year the child began to suffer from epileptic fits, and it was then that her father realized that she was not a normal child and was not using her right arm and leg properly. More precise evidence as to the infant's condition before this date was furnished by observations made in the Sheffield City General Hospital when she was 18 months old. Dr. Clark, the Medical Superintendent, kindly provided the following notes. "The child was sent in as a case of pneumonia but proved to have bronchitis. There was a slight internal strabismus of the left eye, but no other paralysis. She was well nourished, and there was no history of any previous illness. She remained in hospital about three weeks and was discharged well. There was no history of fits."

Family History.—The parents, grandparents, and two older brothers were mentally and physically normal. The twin sib of the patient was found dead in bed when six months old but the father could not say what was the cause of death.

Examination After Admission.—The patient was an idiot with a mental age of two years nine months as estimated by the Merrill-Palmer scale of tests. Speech was limited to a few poorly articulated words. She was often noisy and destructive and took little interest in her surroundings. She was small-headed, and about three years retarded as regards standing stature. The blood Wassermann reaction was negative. Neurological examination gave the following information. The fundi and discs were normal. The pupils were equal and reacted to light and accommodation. There was a left convergent strabismus. A right-sided hemiplegia was present with shortening and wasting of the limbs, the forearm being contracted in the pronated position. Muscle tone was spastic, and the tendon reflexes were exaggerated on the right side, the left knee jerk also being abnormally brisk. The abdominal reflexes were absent. Both plantar reflexes were reported as flexor. She was able to walk but was unsteady. Sphincter control of bladder and bowel was defective. She was a severe

epileptic, the fits being incompletely controlled by phenobarbitone and bromide. Death resulted in her nineteenth year from pulmonary tuberculosis.

Examination of the Central Nervous System

Macroscopic Examination of the Brain.—The weight of the brain was 825 g., cerebellum and pons accounting for 135 g. The transverse dimension of the left cerebral hemisphere was markedly shorter than the right, slight shortening also being present at the occipital pole. The gyri of the left side were generally somewhat smaller and of more variable diameter than those of the right hemisphere, this difference being most noticeable in the parieto-occipital area (Figs. 18, 20). The convolutions in this part of the cortex were more complex and irregular, and sometimes their crowns at points of narrowing appeared sclerosed. The cuneus was markedly stunted. Viewed from the surface the brain showed no evidence of a destructive process, but on section the basal part of individual gyri in the parieto-occipital area often showed considerable shrinkage, and varying degrees of destruction were seen in the walls of the convolutions. The left lateral ventricle was generally dilated, the subcortical white matter in the roof of the posterior horn being reduced to a few millimetres in depth. The frontal part of the body of the left caudate nucleus was considerably thinned and elongated in a lateral direction (Fig. 19). In the white matter of the left frontal lobe, immediately superjacent to the outer and upper angle of the dilated ventricle, a small area of cavitation and rarefaction was present beneath the intact ependyma. The cerebellum showed slight hypoplasia of the right hemisphere.

Microscopic Examination

Cerebral Cortex.—The shrunken parieto-occipital gyri of the left hemisphere showed, in the main, the same microscopic features as those in Case 2, though the numerous small convolutions of bizarre shape were not encountered. Hemiatrophy of individual convolutions was frequently seen, with abrupt transitions between mural areas of destruction and overhanging intact crowns. The anterior wall of the left precentral gyrus, and also the left post-central gyrus in part of its course, were affected in this way, the latter narrowing at its upper limit to an atrophied leaf-like structure. The basally constricted, club-shaped convolutions showed hypermyelinated plaques, gliosis, and conspicuous nerve cell loss in their shrunken portion (Fig. 24). The left visual cortex was atrophied in the depths of the calcarine fissure. In the transitional zone between degenerated and normal portions of the visual area, état marbré was present in the form of narrow strands of hypermyelinated fibres running at right angles to the stria of Gennari (Fig. 22). Linear streaks of gliosis, corresponding in myelin preparations to similar streaks of demyelination, were often seen radiating upwards from the thinned white matter into the central cores of the overlying gyri. This phenomenon was also observed in the small area of cavitation adjoining the frontal horn of the lateral ventricle (Fig. 23). The central white matter of the left occipital lobe was devoid of myelin and showed heavy gliosis (Fig. 22). There was a conspicuous loss of pyramidal cells in the Sommer sector of the left cornu ammonis. No pathological change of note was found in the right side of the brain, with the exception of a small area of complete cortical devastation associated with gliosis, and irregularly arranged hypermyelinated fibres present in the anterior wall of the pre-central gyrus in its upper portion.

Basal Ganglia.—The attenuated part of the body of the left caudate nucleus showed complete disappearance of nerve cells, heavy fibrillary gliosis, and a conspicuous strand of coarse, myelinated fibres running parallel to the ventricular surface. At a point where this atrophic portion expanded frontally to form the head of the nucleus there was an area of typical état marbré in the form of a large triangular hypermyelinated scar having within it an island of normal tissue (Fig. 21). In the thalamus of the left side there were several areas of nerve-cell devastation and gliosis, more particularly in the lateral nucleus, of the type commonly associated with retrograde degeneration following cortical lesions. In the dorsal part of the lateral nucleus, near its ventricular surface, there was a small necrotic focus, characterized by absence of myelinated fibres and a dense undergrowth of fibrillary neuroglia.

Other Parts of the Brain.—The left half of midbrain, pons, and medulla were noticeably smaller than the right. A small focus of tissue destruction, similar to that described in the thalamus, was present in the left side of the midbrain at a point dorso-lateral to the decussation of the superior cerebellar peduncles (Fig. 25). The pyramidal tract of the left side showed marked degeneration, though scattered fibres were fairly numerous in the medullary pyramid, the total volume of which, however, was grossly reduced (Fig. 26). The lateral columns of the right side of the spinal cord were similarly affected throughout their course. The right cerebellar hemisphere and dentate nucleus showed mild hypoplastic changes, as in Case 2.

FIG. 1.—Case 1. Coronal section of basal ganglia of the left side. Note the état marbré in the dorsal part of the putamen and in the anterior nucleus of the thalamus. Anderson's modification of the Kultschitsky-Pal method, × 2·2.

FIG. 2.—Case 1. Coronal section of basal ganglia of the right side. Note the état marbré in the outer part of the putamen and the abnormal mottled appearance of the thalamus (due to areas of myelin poverty in juxtaposition with areas of increased fibre density). Stain as in Fig. 1, × 2·6.

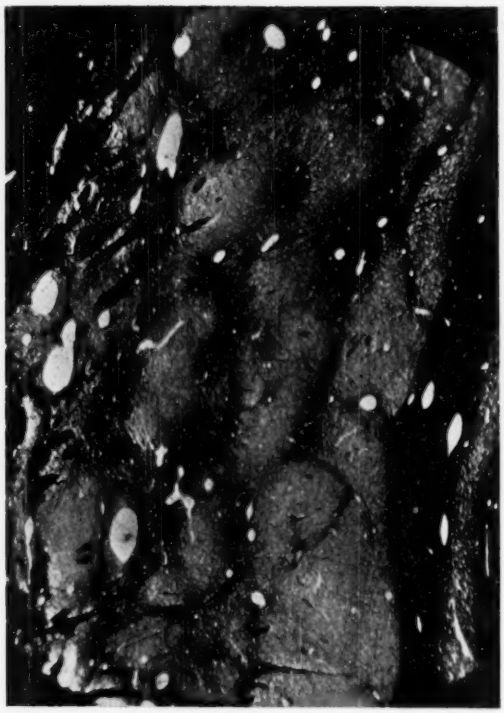

FIG. 3.—Case 1. Left putamen showing état marbré. The normal compact fibre bundles are intact. Anderson's modified Kultschitsky-Pal stain, × 12·8.

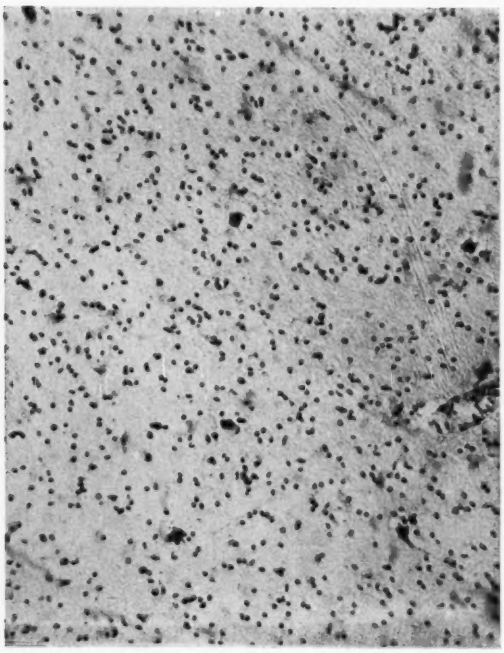

FIG. 4.—Case 1. Left putamen showing gliosis and loss of small nerve cells in an area of marbling. The larger nerve cells are preserved. Toluidine blue, × 100.

FIG. 5.—Case 1. Left putamen. Fibrillary gliosis in an area of état marbré. The field corresponds to that shown in Fig. 3. Holzer stain, × 12·8.

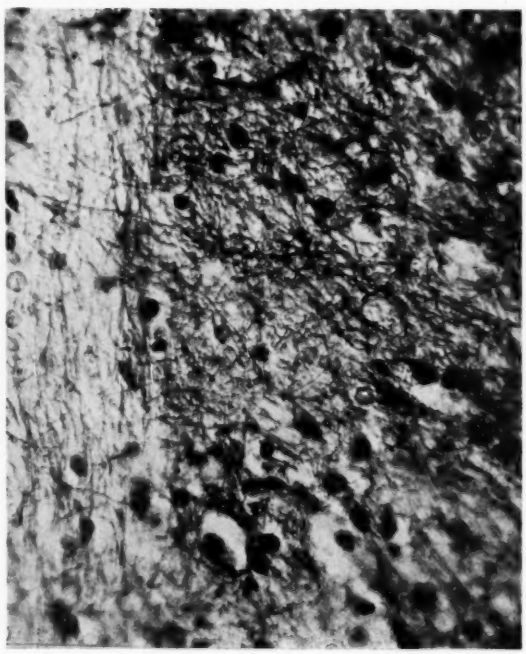

FIG. 6.—Case 1. Left putamen. Fibrillary gliosis in an area of état marbré. On the left is seen part of a normal compact fibre bundle. Holzer stain, × 360.

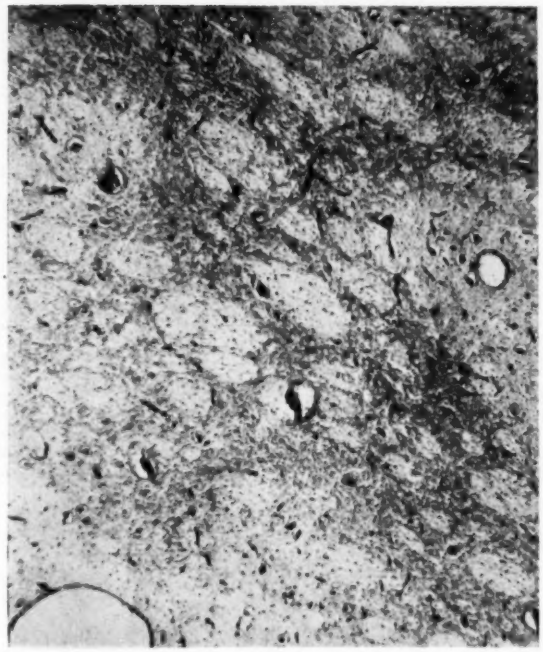

FIG. 7.—Case 1. Left thalamus showing extensive loss of nerve cells and increase of glial nuclei in the lateral nucleus. Toluidine blue, × 36.

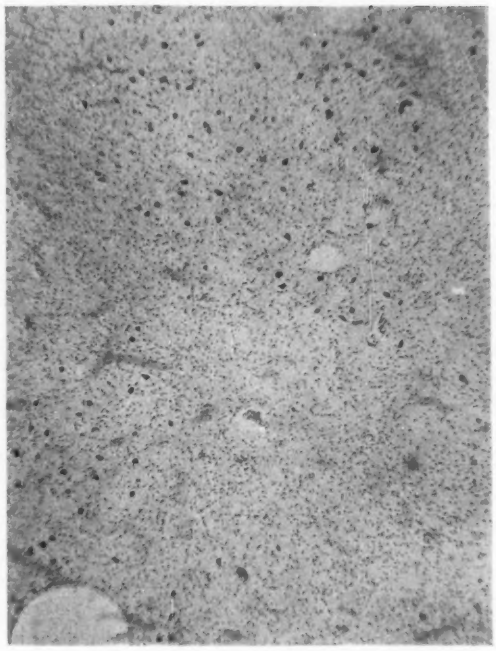

FIG. 9.—Case 1. Left thalamus. Same area as in Fig. 7. Showing reticulate arrangement of the gliosis. Holzer stain, × 36.

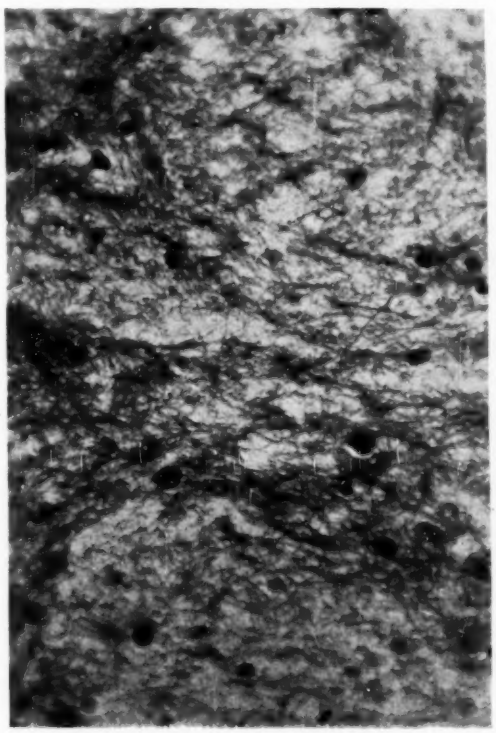

FIG. 8.—Case 1. Left thalamus. Dense fibrillary gliosis in lateral nucleus. Holzer stain, × 360.

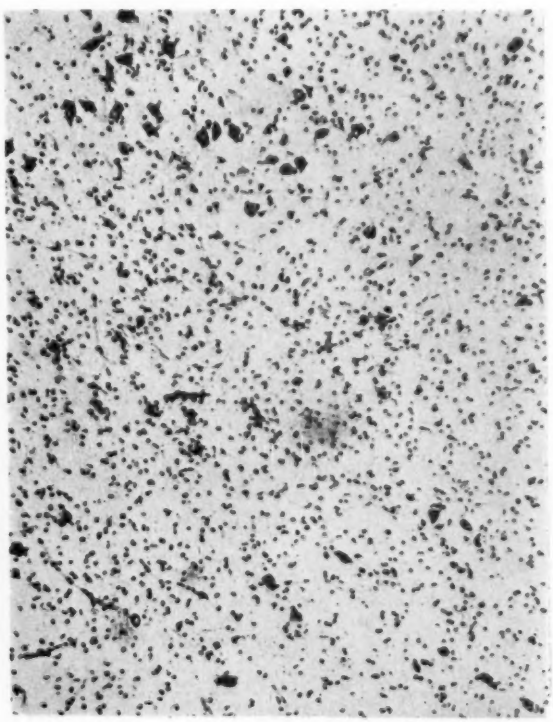

FIG. 10.—Case 1. Left thalamus showing loss of nerve cells and glial proliferation in the area of marbling seen in the anterior nucleus. Note the "calcification" of many of the remaining nerve cells. Cresyl violet, × 80.

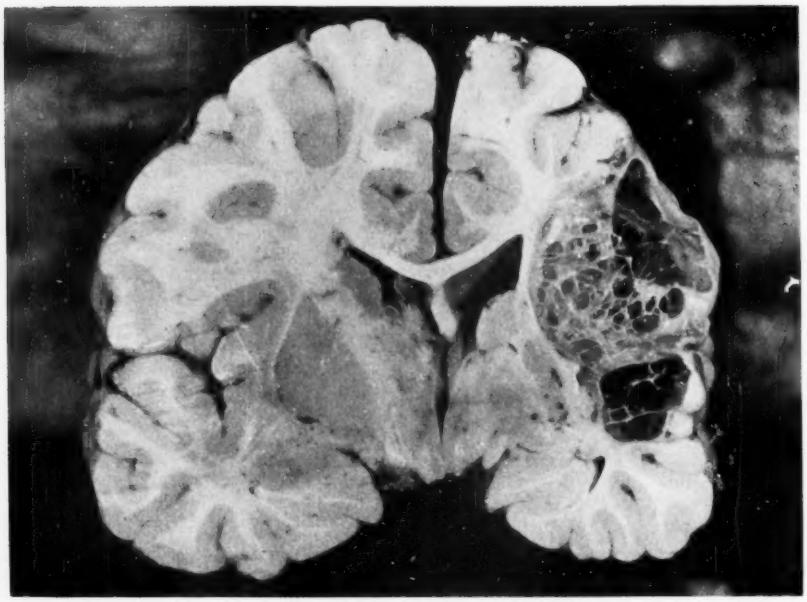

FIG. 11.—Case 2. Coronal section of brain showing maximum extent of the cavitation of the right hemisphere.

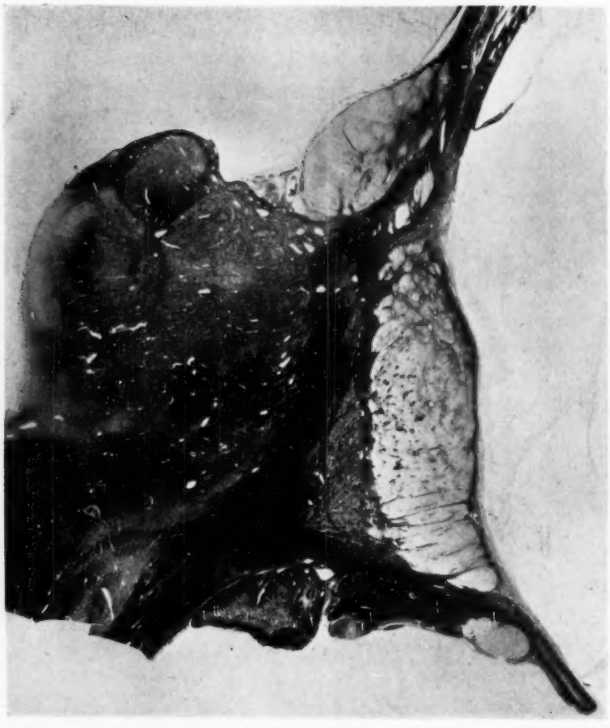

FIG. 12.—Case 2. Etat marbré of the caudate nucleus and dorsal putamen of the right side. The cortex of the insula has been totally destroyed. Anderson's modified Kultschitsky-Pal stain, × 2·8.

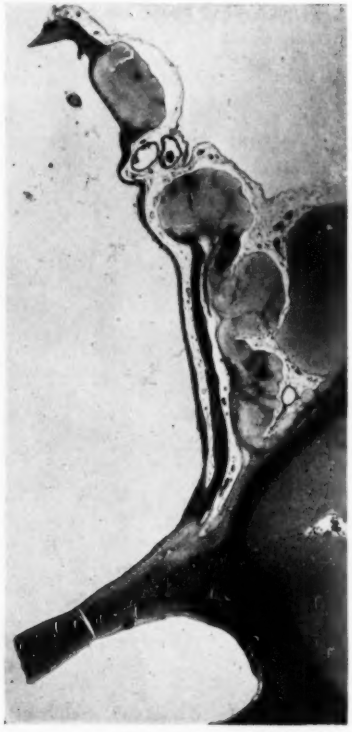

FIG. 13.—Case 2. Section through part of the thin external wall of the cystic cavity in the right hemisphere. Note the island of grey matter in membrane and the distortion and splitting of the gyri on the right. Mallory's phosphotungstic acid haematoxylin, × 3·4.

FIG. 14.—Case 2. Cerebral cortex overlying an area of rarefaction in the right occipital region. Note the islands of nerve cells separated by network of gliosis and the mammillated surface of the gyri ("granular atrophy"). Cresyl violet, × 24.

FIG. 16.—Case 2. Sclerotic hypermyelinated ulegyria adjoining central cavitation of right hemisphere. Note basal constriction of some of the gyri and apparent fusion of adjacent microgyric convolutions. Stain as in Fig. 15, × 5.

FIG. 15.—Case 2. Occipital gyri adjoining the hemispheric cavitation. Note the état marbré of the ulegyria and the absence of myelin in the basal part of the convolutions. Anderson's modified Kultschitsky-Pal stain, × 3·5.

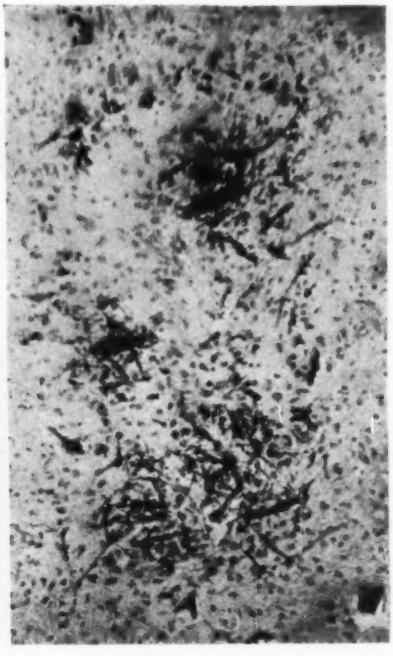

FIG. 17.—Case 2. Focus of nerve cell loss and gliosis in the right globus pallidus with abundant "calcified" débris and nerve cells. Toluidine blue, × 100.

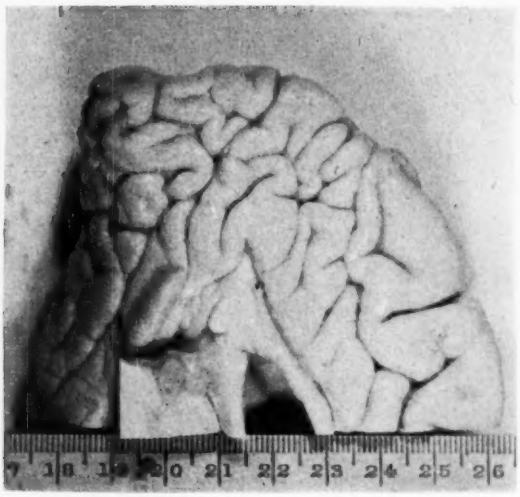

FIG. 18.—Case 3. Medial surface of left occipital lobe showing narrow gyri of complex arrangement (cf. Fig. 20).

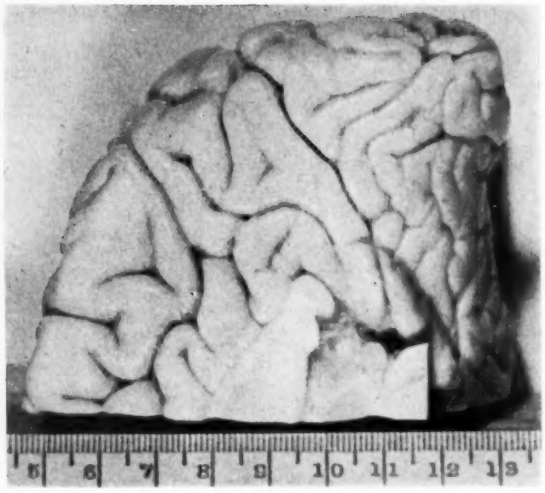

FIG. 20.—Case 3. Medial surface of right occipital lobe for comparison with Fig. 18.

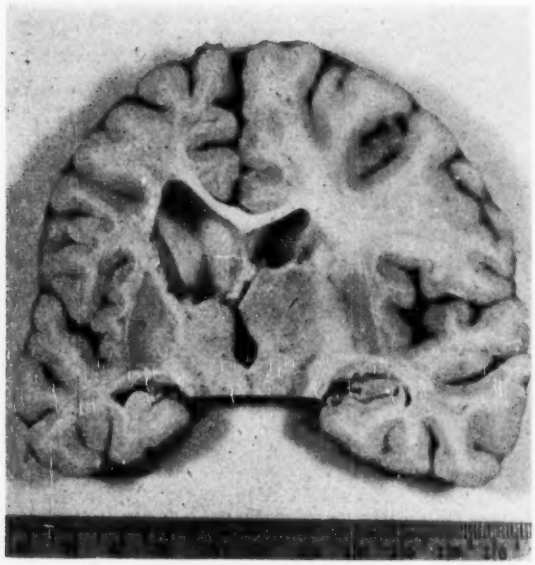

FIG. 19.—Case 3. Coronal section of brain through middle of thalami. Note dilated lateral ventricle, thin central white matter of left hemisphere, atrophy of left caudate nucleus and thalamus.

FIG. 21.—Case 3. Etat marbré of head of left caudate nucleus. Anderson's modified Kultschitsky-Pal stain, × 24.

FIG. 22.—Case 3. Coronal section through left occipital pole showing absence of myelin in much of the central white matter. Note hemiatrophy of a gyrus and the atrophy of the basal part of the calcarine cortex. Anderson's modified Kultschitsky-Pal stain, × 2·7.

FIG. 23.—Case 3. Subependymal cavitation with surrounding poverty of myelin found adjacent to the frontal horn of the left lateral ventricle. Note on the left the "Y"-shaped area of necrosis with thin prolongations entering the central cores of the frontal gyri. Stain as in Fig. 22, × 2·9.

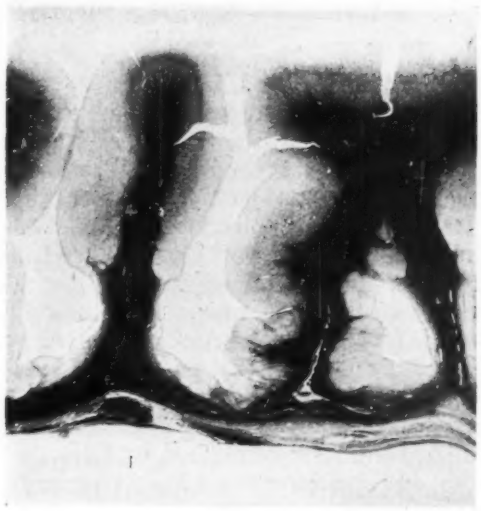

FIG. 24.—Case 3. Ulegyria of left occipital lobe. Note the very thin and poorly myelinated subcortical white matter, the basal atrophy of gyri with thin central streaks of non-myelinated tissue, and the hypermyelinated plaques in the transition zone between atrophied and normal cortex. Stain as in Fig. 22, × 3.

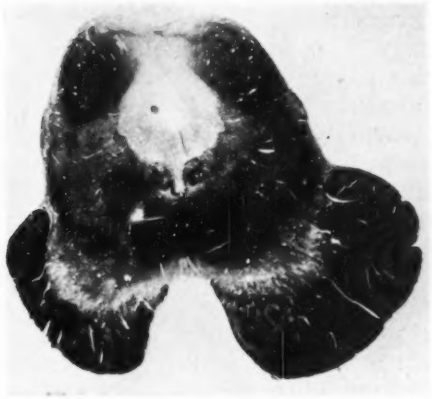

FIG. 25.—Case 3. Midbrain. Note hypoplasia of left side and small round area devoid of myelin at the left side of the decussation of the superior cerebellar peduncles (not an artefact). Stain as in Fig. 22, × 2·1.

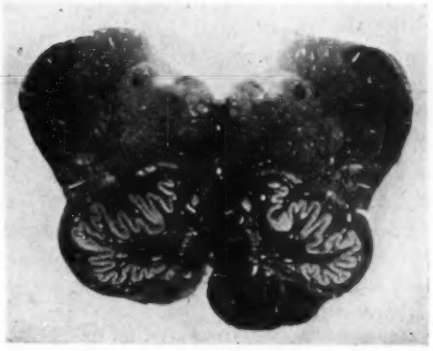

FIG. 26.—Case 3. Medulla showing small left pyramid which is not completely degenerate. Stain as in Fig. 22, × 2·7.

Comment

The pathological findings in the first case give no support to Alexander's (1942) theory that état marbré is a prenatal malformation due to aberrant fibres from the fronto-pontine tract ramifying in the corpus striatum. The obvious nerve-cell devastation of the areas of marbling, the associated fibrillary gliosis, the widespread implication of both thalami with frequent "calcification" of nerve cells and patchy neuroglial sclerosis, point rather to a vascular pathogenesis as postulated by Scholz *et al.* (1938). According to this view, hypermyelination of nerve fibres is the expression of a disturbance of glial function conditioned by the partial anoxia of the tissues of the area concerned. When, moreover, the regions affected by état marbré correspond to the periventricular drainage area of the vulnerable Galenic vein, when there are found associated with this marbled state lesions of a grosser kind compatible with the theory of a vascular pathogenesis, and when the clinical history records the infant's severe asphyxia after abnormal parturition, it would seem perverse to seek further than birth injury for the primary cause of the condition.

The association in Case 1 of an intact cerebral cortex with gross reduction in intelligence is a seeming paradox. While an accurate estimate of mental ability is difficult to make in an individual with severe dysarthria and in whom mobile spasm makes performance tests impracticable, it is well known that, given appropriate training, or sometimes even without this, some of these unfortunate patients are able to surmount their physical handicaps in an astonishing way and show a pertinacity of effort incompatible with the presence of mental defect. One such patient of normal intellect at present at Stoke Park, with arms entirely useless on account of severe athetosis, and unable to climb stairs because of spasm of the thigh muscles, is nevertheless able to use his toes for writing, manipulating a spoon, and for lighting and holding a cigarette. Perhaps in such persons the nerve cell loss is minimal and confined to the extra-pyramidal motor system, whereas, in the present case, the poor development of cortical function implicit in the patient's imbecility may be attributed to the coincidental widespread lesions of the thalami and the consequent interference with their cortical projection systems.

In the second case, the history of the birth is highly suggestive of trauma, forceps having been applied in a primipara six hours after the onset of labour and the infant's apnœa having been treated by a crude and now obsolete method likely to aggravate venous congestion in the head. The postnatal story of the baby's apathy and weakness, epilepsy and hemiplegia subsequently becoming manifest, is also typical of birth injury. The survivors of such tragedies of domiciliary midwifery are collected together in colonies for mental defectives and doubtless form a considerable proportion of their paralysed population. From the pathological standpoint, the large trabeculated cystic cavity involving much of the central white matter of the hemisphere is typical of the late consequences of multiple confluent hæmorrhages or anæmic necrosis due to venous congestion and stasis during birth (Schwartz, 1924; Benda, 1945). The bizarre hypermyelinated ulegyria seen at the edges of this central porencephaly is of the same type as that previously described in cases of birth injury (Norman, 1944) and need not be discussed again in detail here. The état marbré found in the putamen and caudate nucleus of the porencephalic hemisphere resembled the variety described by Alexander in that an accompanying gliosis was virtually absent, or, at least, was not effectively demonstrated either by the Holzer or Mallory methods. Yet the association of striatal marbling with obvious destructive lesions of the cortex and globus pallidus of the same side surely discounts the possibility of a double pathology. It would seem that only by an exclusive preoccupation with examples of état marbré confined to the striatum and unaccompanied by gliosis may the theory of primary malformation be seriously entertained. The small focus of necrosis in the globus pallidus containing ferruginous débris is of interest, since demyelination of part or all of the globus pallidus, sometimes with excessive deposition of the Hallervorden-Spatz pigment has not infrequently been encountered in conjunction with état marbré of the basal ganglia. In the present instance the lesion was a minimal one resembling those found in the thalamus and midbrain of Case 3, and was probably due to a small hæmorrhage. The combination of cortical softening with état marbré of the basal ganglia accounts for the frequent occurrence of some degree of athetosis in the affected hand of some young hemiplegics, infantile hemiplegia differing in this respect from the adult form. That athetosis was not observed in the present case is not surprising considering the extent of the damage to the cerebral cortex, preservation at least in part of the pyramidal tract being a necessary prerequisite for the exteriorization of mobile spasm.

In the third case the pathological findings were diverse: a stunted left hemisphere with relatively narrow and tortuous gyri showing widespread hypermyelinated lesions in the parieto-occipital region, unilateral dilatation of the whole of the lateral

ventricle of the affected side, atrophy of the body of the left caudate nucleus (état fibreux of the Vogts) merging into état marbré in the region of the head of that nucleus, small foci of necrosis in the left thalamus and midbrain, and, most important of all from the standpoint of pathogenesis, paraventricular softening of the central white matter in the left frontal lobe. The latter finding, in the light of Schwartz's observations, may be regarded as pathognomonic of the terminal vein lesions of birth injury and was present also in the first of three cases of birth injury recently published by myself (1944), where the distribution of lesions closely resembled those of the case now under consideration. Yet from the clinical history it would appear that the onset of hemiplegia was delayed, certainly until after the age of eighteen months and probably until about the age of three years, when epileptic fits commenced. Such a history is not usually regarded as suggestive of birth injury, and a hypothetical inflammatory cause, the so-called encephalitis of Strümpell, is often invoked to account for the subsequent hemiplegia. The fact, however, that the onset of infantile hemiplegia is more common the nearer the age of the infant approaches one year and becomes much rarer after the age of six (Taylor, 1905) points to a causal factor operative with maximum intensity in early infancy, and it is likely that birth injury plays some part in the undoubtedly complex ætiology of this group of encephalopathies. It may be supposed that in these delayed forms of birth palsy the original lesions spare sufficient cortical tissue to mask for the time being the inherent instability of the infant's motor apparatus. As time passes, however, sclerosis occurs in the damaged parts of the brain, epileptogenic foci are formed, convulsions begin, and the associated vascular changes wreak further permanent injury upon the cortical inhibitory centres, with resulting hemiplegia which may be either ingravescent or sudden in its mode of development.

Summary

The clinical and neuropathological features presented by three mental defectives whose brains showed the common feature of état marbré of the corpus striatum have been described. It has been shown that a conspicuous fibrillary gliosis and nerve-cell loss may be present in the areas occupied by the hypermyelinated fibres of the striatum. Etat marbré of the corpus striatum may be associated with widespread destructive lesions elsewhere in the brain, particularly in the cerebral cortex where hypermyelinated ulegyria occurs at the margin of areas of cystic degeneration of the subcortical and central white matter. Lesions of thalamus, globus pallidus, and midbrain, suggestive of a vascular pathogenesis, were also found in these cases. A form of delayed hemiplegia following birth injury has been described. It is concluded that in these cases the vascular lesions set up by abnormal parturition have been inflicted mainly upon the venous side of the cerebral circulation and that état marbré of the corpus striatum and elsewhere is only one of the many possible sequelæ of partial anoxia of the tissues conditioned by birth trauma.

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"PINS AND NEEDLES": OBSERVATIONS ON SOME OF THE SENSATIONS AROUSED IN A LIMB BY THE APPLICATION OF PRESSURE

BY

G. WEDDELL and D. C. SINCLAIR

From the Departments of Anatomy and Orthopaedic Surgery, University of Oxford

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Introduction

WHEN the limb of a normal subject is compressed by means of a sphygmomanometer cuff inflated to a pressure beyond the systolic blood pressure, a series of spontaneous sensations can be produced in it, both during and after the release of pressure, provided the compression lasts long enough. Investigators in the past appear to have paid little attention to such sensations, although some of these, under the generic term of "pins and needles", are a common feature of everyday life. In 1931, Lewis, Pickering, and Rothschild published an account of the sensory changes occurring during and after compression of the arms of normal subjects by sphygmomanometer cuffs. At the end of this comprehensive paper is given a description of a "form of tingling", occurring after release of compression, which was investigated by the authors, together with some general conclusions as to its nature and the mechanism of its production.

It appeared possible that an investigation of the sensations experienced as a result of compressing the arm might throw some light on the mechanism by which spontaneous pain originates in the human body, and accordingly it was determined to repeat and amplify the observations of Lewis and his collaborators with this end in view. The present paper gives an account of some investigations on the subjective sensory phenomena associated with compression of the upper limb by means of a sphygmomanometer cuff.

Technique

Ordinary sphygmomanometer cuffs, 12 cm. in width, were used, and inflated to a pressure of 150 mm. Hg for varying times in varying situations on the upper limb. In order to determine the effect of the degree of compression on the results, a few experiments were done with pressures ranging from 60 mm. Hg to 300 mm. Hg, but 150 mm. Hg was selected as standard since it was well above the systolic pressure in all our subjects, and did not cause undue discomfort. The pressure was thrown into the cuff by pumping up the instrument in the usual way, but as rapidly as possible. The time taken to reach 150 mm. Hg pressure by this means was usually less than 3 seconds. At the end of compression the rubber tube was disconnected, and the pressure fell to zero in approximately 1 second. The armlet was then rapidly removed. The experiments were, in general, done at room temperature, which throughout the period of the investigation varied between 17° C. and 22° C. A few observations were also made on one subject with the limb immersed in a thermostatically controlled water-bath at 37° C. In the experiments at room temperature, care was taken, so far as possible, to exclude draughts.

It was thought that, if any of the sensations produced were wholly or partly due to events taking place in the periphery of the limb, localized pressure on any area of skin in the periphery might modify the results. Accordingly, throughout each compression the arm was allowed to hang down vertically so that no part of the limb compressed made contact with other objects. No special attention was paid to the condition of the limb before compression, except that the pressure was always applied with the arm at the side and the elbow bent to a right angle, to avoid any undesirable congestion of the limb. Immediately after release of the pressure the elbow was again bent to a right angle to facilitate observations. Timing was done with a stop-watch, which could not be read by the subject of the experiment. The main bulk of the work was done by the authors, using each other as experimental subjects, but every experiment reported in this paper has been confirmed on at least one other subject. The total number of subjects examined is 16; of these 7 were normal in all respects, and 9 had various pathological changes involving one upper limb.

In the case of all subjects other than the authors, no indication was given by the experimenter as to what sensations might be expected during or after compression; they were merely told to observe the compressed limb

closely and to report any sensations they might feel as soon as these arose. As soon as any sensation was reported, the time was noted, and the subjects were then questioned as to the exact nature, intensity, and distribution of the sensation, records being made of the subjects' own words. They were then warned that the sensation might or might not disappear, and were asked to give the end-point as accurately as possible if it did disappear. This procedure, which was unavoidable if the effects of suggestion were to be eliminated, caused one or two of the untrained observers, who had no idea what to expect, to fail to report a given sensation until it was fully established, instead of reporting it as soon as it became just perceptible. In such cases the experiment was repeated after a suitable interval. This technique differs in some respects from that adopted by Lewis *et al.* (1931). Though these authors do not explicitly state the position of the limb during experimentation, it can be inferred that it lay horizontally in a water-bath. This bath was kept at a constant temperature of 35° C. throughout. It will be seen later that in spite of these differences comparable results were obtained.

Sensations Aroused

Before discussing the results of individual experiments, it is desirable for clarity to give an account of the subjective sensations produced during and after compression of the arm just above the elbow by a sphygmomanometer cuff at 150 mm. Hg. This summary represents the general experience of the authors, and is based on consideration of the notes of all the subjects so far tested. In any compression at this site in a normal limb, providing (a) the compression is of sufficient duration, and (b) no compression has been done on the arm for at least 2 hours previously, three types of sensation can be elicited almost invariably.

1.—A characteristic tingling (" compression tingling ") in the hand, coming on between 1 and 2 minutes after compression has started, and lasting an average of 3 to 4 minutes. This tingling has been variously described as " a faint comfortable soda-water sensation ", " a buzzing ", " a fine light tingle ", " ants running up and down inside the skin ", etc. In some cases a few sharp pricking elements have been reported, but in the main the sensation appears subjectively to be composed of " bright " touch impulses, and the general effect produced is one of touch rather than pain. The sensation begins gradually, builds up to a maximum, and gradually fades away. External stimuli, such as touching or rubbing the fingers, do not modify " compression tingling " in any way. There is usually very little difficulty in giving an accurate time for the onset of the tingling, but its disappearance is more difficult to fix precisely, and this time has in all cases been taken to the nearest quarter of a minute.

2.—A " velvety " sensation (" velvety numbness ") arising much later, rarely before 13 minutes and usually after 15 minutes from the initiation of compression. This sensation is usually not spontaneous at first, but can be elicited by light touch, stroking, or pressure. It appears first in the tips of the fingers and spreads proximally up the hand fairly rapidly. It gives the impression that the finger is touching the pile of a very fine velvet, and, though it has no apparent pain component, it gives rise to a peculiarly unpleasant subjective interpretation of a sickening character. After prolonged compressions (over 16 minutes), and in cases where compressions are repeated at short intervals, this sensation may become spontaneous. No compressions in this series have been of longer duration than 20 minutes, and in all cases where " velvety numbness " has been aroused it has persisted until the release of compression or some time later—on occasions for as long as 45 seconds after release. It is possible, however, that if compression were maintained for longer periods the sensation would subside before release.

3.—A very strong coarse pricking (" release pricking ") which arises in the hand after the compression is released and lasts for a variable time depending on the length of compression. This is completely characteristic, and differs from the " compression tingling " in being much coarser, having a component of large numbers of sharp bright pricks, as of a needle entering the skin, and in being interpreted subjectively as pain rather than touch. The invariable description of the sensation given by untrained subjects was " pins and needles ". On being pressed for a closer description, they gave one of two replies : "like a lot of sharp needles going vertically through the skin " or " like a lot of small electric shocks ". No subject had the slightest difficulty in distinguishing subjectively between the initial phase of the " release pricking " and the " compression tingling ". The sensation was described as " painful " in all cases, but only 3 of the 16 subjects gave an affirmative reply to the question " Would you like to get away from it if you could ? " The others, including the authors, considered that while the sensation was undoubtedly painful, there was no unpleasant affective component, and the total emotional attitude to the sensation was one of interest rather than pain. There is, however, a considerable underlying touch component in the release pricking, which is evident from the first as a continuous diffuse tingling sensation in between the pricks. Initially this is not readily perceived, owing to the insistence with which the pricks engage the attention, but after some time, depending on the duration of the compression, the pricks " die down ", leaving a general tingling sensation difficult to distinguish from compression tingling. This in its turn fades very gradually indeed, so that the exact end-point when sensation in the hand again becomes normal is difficult to determine. In spite of this difficulty,

however, repeated experiments indicate that, though the interpretation of the end-point may vary from subject to subject, the time given is remarkably constant in the same individual. This time has in all cases been taken to the nearest quarter of a minute. The onset of the pricking is in all cases definite and sharp, and can be given with an accuracy of a few seconds after compressions of 10 minutes or longer. It is found that, previous to the onset of spontaneous pricking, the same sensation can be induced by lightly tapping the fingers against a solid object. Similarly, after cessation of the spontaneous tingling which follows the disappearance of the pricking, tapping will usually revive the tingling for a little longer. The times given for the duration of release pricking in this paper include the short periods, both before and after the time of spontaneous sensation, during which the sensation can be produced by external stimuli such as tapping or rubbing the fingers. During the period of spontaneous pricking, such stimulation temporarily greatly increases the intensity of the sensation, a shower of pricking impulses being produced locally and, though to a lesser extent, throughout the distribution in which the release pricking is felt. Once established as a spontaneous sensation, the release pricking mounts rapidly to a plateau of intensity, then gradually fades, as previously described.

In addition to these three clearly defined sensations, several others may be aroused in the limb during compression. These do not invariably occur, and, when they do, there is considerable variation in their time of appearance and duration. All subjects reported an aching discomfort under the pressure cuff, which gradually became less marked as the experiment proceeded. In some cases this ache spread to include the elbow and a small area of the forearm just distal to the cuff. In several subjects the hand felt " tight " and " swollen " during compression, and two reported a well marked aching pain " deep in the wrist". Another two subjects consistently felt a diffuse vague ache in the area in which compression tingling was felt. This ache came on gradually during the tingling, and eventually replaced it : in both cases the ache persisted until release of compression. Vague transient feelings of cold and warmth often occur during compression ; they are usually diffuse and felt chiefly on the back of the hand. One of us, however (G. W.), has experienced definite punctate flashes of cold on the back of the hand. These waves of temperature sensation are to be distinguished from the generalized cold sensation which comes on in a prolonged compression, and is accompanied by a considerable fall in skin temperature.

On release of pressure after moderately long compressions a fairly definite sequence of temperature sensations is felt almost immediately. The first of these is a wave of warmth which appears to " hit " the hand almost as soon as compression is released. This is succeeded abruptly by a strong sensation of cold, which then gradually " swells " into a warm glowing comfortable feeling. The whole sequence takes place in about 15 seconds, and precedes the onset of release pricking. It is interesting that flushing of the hand does not occur until about 15 seconds after release, which is about the time of onset of the warm glowing feeling. Of these release temperature sensations, only the warm glow is invariable, but the above sequence has been reported by several subjects. The sensations of warmth and cold last a few seconds only, and may readily be overlooked by an untrained subject.

The investigations reported in this paper have been carried out with the object of elucidating the nature and mechanism of production of compression tingling and release pricking, these sensations being subjectively characteristic, reproducible in distribution, quality, duration, and intensity in the same subject, and reproducible to a considerable degree in distribution, quality, and duration from subject to subject.

Reproducibility of Sensations

INDIVIDUAL VARIATION.—No figures can, of course, be quoted to show the reproducibility of the compression tingling and release pricking in quality and intensity. It may be said, however, that in any given subject these are practically constant for any given length of compression. Some figures may be adduced to indicate the degree of reproducibility of the sensations in time. The table gives the mean times of appearance and the mean durations of compression tingling and release pricking in 4 subjects as a result of 10-minute compressions of the arm. In subject 1 the figures are the mean of 8 such compressions ; in the remainder, the mean of 4 experiments. In all cases no compressions had been done on the arm for more than 2 hours previously.

As stated above, the times of disappearance of both compression tingling and release pricking have been taken only to the nearest quarter of a minute. Accordingly, these times and standard deviations in the table are given only to the nearest 5 seconds. The figures show that of the two sensations, release pricking is the more exactly reproducible in time, both in the same subject and from subject to subject. There are, nevertheless, considerable differences in the duration of both sensations from subject to subject, and the relatively high standard deviations for the duration of compression tingling demonstrate the variability of the duration of this sensation in the same subject. For these reasons it was necessary, in any experiment dealing with the timing of these sensations, to control the observations by direct reference to the other arm of the same subject. In most subjects it was possible to take several such control readings to establish normal mean values, but

TABLE.—MEAN TIMES OF APPEARANCE AND MEAN DURATIONS OF COMPRESSION TINGLING AND RELEASE PRICKING IN 4 SUBJECTS AS A RESULT OF 10-MINUTE COMPRESSIONS OF THE ARM

Subject	Compression tingling		Release pricking	
	Mean time of onset (after compression)	Mean duration	Mean time of onset (after release)	Mean duration
1. D. S.	1′ 42″±20″	3′ 30″±55″	50″±4″	5′ 45″±15″
2. G. W.	1′ 04″±18″	4′ 55″±15″	50″±1″	4′ 55″±35″
3. R. M. W.	1′ 18″±9″	5′ 45″±45″	47″±5″	4′ 15″±20″
4. L. D. B.	1′ 13″±3″	3′ 40″±20″	60″±3″	4′ 10″±15″

in some of the subjects with pathological conditions only one control observation could be made.

EFFECT OF ENVIRONMENTAL TEMPERATURE.—In one subject (D. S.) inspection of the records of 85 compressions experiments in which the room temperature was carefully recorded failed to show that variation in the air temperature between 17° C. and 22° C. had any effect on either sensation. Several 16-minute compressions of the arm were done on this subject, the limb being placed in a thermostatically controlled water-bath at 37° C. for 2 minutes before compression, and maintained vertically in the bath during compression. Comparison of these experiments with other 16-minute compressions done at the same level on the same subject at room temperature failed to show any difference in the intensity, distribution, quality, and duration of the sensations. As a check on this observation, the left arm was placed in a water bath at 37° C., the right arm being at room temperature (18° C.). Both arms were then compressed simultaneously. No difference in the sensations experienced in the two limbs could be detected. Repetition of this experiment on two other normal subjects gave precisely similar results. No other environmental factors were investigated.

For the remainder of the paper compression tingling and release pricking will be considered separately, as it will be seen later that they are evidently due to different mechanisms.

Observations on Compression Tingling

EFFECT OF SITE OF COMPRESSION.—It has been found that, for typical compression tingling to be produced, the cuff must be above the elbow. In four subjects so far tested to establish this point, while compression above the elbow invariably produced the sensation, compression at any level distal to the elbow almost invariably failed to produce it. One subject, however (G. W.), has occasionally felt a very feeble tingling as a result of a compression of the forearm just below the elbow.

EFFECT OF DURATION OF COMPRESSION.—As previously stated, compression tingling begins between 1 and 2 minutes after compression is instituted, and lasts for 3 to 4 minutes before spontaneously fading. If the pressure is released while tingling is being experienced, the sensation completely disappears in a matter of a few seconds, irrespective of the stage of tingling at which release occurs.

DISTRIBUTION OF SENSATION.—Compression tingling is felt mainly in the hand: in none of the 16 subjects tested did it extend more than 2 inches above the wrist joint. It is invariably felt more strongly on the palmar surface than on the dorsal surface, but there is no evidence of any gradation of the sensation in a proximo-distal direction. In this respect compression tingling differs considerably from release pricking, as will be seen later. In 11 of the 16 subjects the tingling was felt diffusely throughout the hand, and involved the whole of the palmar surface of the hand and fingers, sometimes extending a little above the ulnar side of the wrist. In 3 of these 11 subjects tingling invariably began in the distribution of the ulnar nerve, and gradually spread to involve the rest of the hand. It should be noted that in no subject examined did tingling occur in the area supplied by the radial nerve. Two of the remaining 5 subjects experienced tingling confined to the ulnar distribution and the terminal phalanx of the thumb, while in the other 3 tingling was rigidly restricted to the area supplied by the ulnar nerve, which could, indeed, be readily mapped out in consequence.

EFFECT OF MODIFICATION OF LOCAL CONDITIONS.—As already stated, compression of the arm above the elbow by a cuff pressure of 150 mm. Hg invariably produces compression tingling. It is found, however, that compression tingling, differing from the "normal" sensation only in being slightly reduced in intensity, can be elicited by a cuff pressure of 100 mm. Hg. On the other hand, a pressure of 60 mm. Hg fails to arouse it. Pressures greater than 150 mm. Hg, up to a maximum of 300 mm. Hg, are

found to give rise to compression tingling in all respects identical with that produced by a pressure of 150 mm. Hg. It may, therefore, be said that the pressure " threshold " necessary to produce compression tingling lies somewhere between 60 and 100 mm. Hg, and that the full response occurs at a pressure of 150 mm. Hg, no further increase in pressure beyond this level having any effect on the sensation.

The " normal " sensation described above is obtained by compressing a cylinder of the arm 12 cm. long. If two overlapping cuffs are placed on the arm above the elbow and inflated together so as to compress a cylinder of the arm approximately 20 cm. long, the resultant compression tingling is indistinguishable in all respects from the normal response. Similarly, if the length of the limb compressed is reduced to 1 cm. by employing an ordinary roller bandage wound round the arm at a tension just sufficient to obliterate the radial pulse, a " normal " result is again obtained.

EFFECT OF MODIFICATION OF PERIPHERAL CONDITIONS.—If the circulation to the hand and forearm is impeded by a cuff just below the elbow maintained at 150 mm. Hg for 16 minutes, no tingling is produced during compression. If now another cuff be placed just above the elbow and inflated to 150 mm. Hg 10 minutes after the start of the distal compression, without releasing the distal cuff, a normal compression tingling results at the usual time after applying the upper cuff, and lasts for the normal period.

EFFECT OF REPEATED COMPRESSIONS.—If a regular series of compressions is made on the same arm at intervals of less than 2 hours, the onset of compression tingling tends to become more and more delayed in each successive compression. At the same time the intensity of the sensation becomes progressively less and less, till, after several compressions, it can no longer be elicited. The shorter the interval between compressions, the more rapidly does this diminution and eventual disappearance of compression tingling occur. For example, in a series of 10-minute compressions, with an interval of 10 minutes between each compression (cycle interval, 20 minutes), tingling can usually be elicited in the first two or three compressions, but by the fourth or fifth compression the sensation produced is no longer a tingling, but merely an abnormal " awareness " of the area in which the tingling is usually felt. Later compressions evoke no sensation whatever. If, on the other hand, 80 minutes are allowed to elapse between individual 10-minute compressions (cycle interval, 90 minutes), an adequate reproduction of the original tingling may be obtained for four or five compressions, but thereafter the sensation " fades " in the same manner, though much more gradually. Because of this phenomenon, in the investigation of compression tingling, compressions were not repeated on the same arm unless an interval of 2 hours had elapsed since the last compression.

SITE OF ORIGIN OF THE IMPULSES.—It is clear that the impulses of compression tingling must arise in the nervous tissues of the limb peripheral to the upper margin of the stretch of limb directly compressed. Theoretically, therefore, they could arise in several sites : (a) at the peripheral nerve endings ; (b) in the main nerves peripheral to the compression cuff ; (c) in the nerves directly pressed on by the cuff ; (d) in a combination of the above sites.

The first of these possibilities need only be considered briefly. It has been noted that, in three of the subjects tested, compression tingling is restricted to the area supplied by the ulnar nerve. It is difficult to conceive of any factor involving the peripheral nerve endings which would selectively affect all those in the ulnar area without also affecting those in the median and radial areas. Direct evidence that the peripheral nerve endings are not the site of origin of compression tingling was obtained by compressing the arm of an individual (subject 8) whose forearm had been amputated 6 inches below the level of the olecranon eighteen months previously. Though this man had not felt his " hand " for 9 months, within 30 seconds of compression a complete phantom hand became evident, and the fingers began to " move ". Two minutes after compression began, tingling, indistinguishable from that felt in his control arm, appeared in the whole of the palmar aspect of the missing hand, and lasted for 7½ minutes. In the control arm tingling began at 2½ minutes and lasted for 5½ minutes. Similar results were obtained in another case of amputation through the forearm (subject 9). The findings in these two subjects, while they exclude the peripheral nerve endings as the site of origin of the impulses, still leave the possibility that compression tingling arises either in the nerves under the cuff, or in the nerves distal to the cuff, or in both sites.

If the tingling arises in the nerves peripheral to the cuff, then alteration of the condition of those nerves by compression would be expected to influence the results. It has been seen, however, that, even after ten minutes' compression of the limb below the elbow by a cuff at 150 mm. Hg, a normal compression tingling may be obtained by applying a second cuff immediately above the first. Further evidence against the site of origin of compression tingling being located distal to the compression cuff was

obtained by carrying out a series of 10-minute compressions on the same limb, the arm just above the elbow and the forearm just below the elbow being compressed alternately. The cycle interval was 25 minutes, and thus the cycle interval for successive compressions of the arm was 50 minutes. Now the tissues distal to the proximal cuff were in this case subjected to the effects of compression every 25 minutes, and, if the compression tingling produced by the arm compressions is due to impulses taking origin in these tissues, it would be expected to "fade" in a manner characteristic of a 25-minute cycle. It was found, however, that the tingling produced by the successive compressions above the elbow" faded" and disappeared in a manner characteristic of a cycle interval of 50 minutes rather than 25 minutes. The inference can be drawn that the tingling is due to impulses produced in the nerves directly pressed on by the cuff, rather than in the nerves peripheral to the cuff.

The findings, therefore, are strongly in favour of the suggestion that compression tingling is due in its entirety to impulses produced in the nerves directly pressed on by the compression cuff. On this hypothesis the differences in the distributions of the sensation in different subjects may be readily explained. The radial nerve, lying deeply under cover of powerful muscles, would not be expected to be so readily affected as the median and ulnar nerves, and of the latter two, the ulnar, being liable to compression against the medial intermuscular septum, is probably the more vulnerable.

The differences observed according to the site of compression still remain to be explained. From the anatomical configuration of the limb just below the elbow it is clear that the nerves are less vulnerable to the effects of compression at this site than they are in the arm. In spite of this, however, a minimal compression tingling has occasionally been elicited by a cuff below the elbow in one subject (G. W.). At the wrist the ulnar and median nerves are again well protected by their position in relation to the bones, but it is more difficult to understand why the superficial branch of the radial nerve does not show the effects of compression. It will be seen later that, in order to produce compression tingling, it is necessary to compress an adequate length of nerve, and the escape of the radial nerve in this situation is probably due to the fact that an insufficient length of nerve is pressed upon.

MECHANISM OF PRODUCTION.—If the impulses originate in the nerves under the cuff they could, theoretically, be produced in several ways : (a) by stimulation of the nerve trunk caused by (i) mechanical deformation, (ii) oxygen lack, (iii) accumulation of local metabolites ; (b) by a lowering of the threshold to stimulation of the nerve due to one or more of the above causes ; (c) by a combination of these factors.

Any cuff experiment necessarily involves both mechanical deformation of the nerves and interruption of their blood supply, and it is difficult to separate the effects of these two factors. Accordingly, further information was sought by compressing directly varying lengths of individual nerves.

In the first series of experiments the ulnar nerve at the elbow was compressed against the medial epicondyle of the humerus by leaning the elbow on a thin, round ruler placed between the medial epicondyle and the olecranon, the elbow being bent to a right angle. By this means a very short length of nerve, of the order of 0·5 cm., was directly compressed, while the circulation to the periphery was completely unimpeded. Similarly, a short stretch of the lateral popliteal nerve was compressed against the neck of the fibula by crossing the legs and thus bringing to bear the pressure of the lateral condyle of the opposite femur. Repeated experiments with both nerves in three subjects failed to elicit any compression tingling. In these experiments it is definite that the nerves concerned were directly pressed upon, since continuance of the same pressure led eventually to complete paralysis of the muscles which they supply, and loss of light touch sensibility over their cutaneous distribution. Attempts were then made to increase the length of ulnar nerve compressed by leaning the elbow on a thin strip of wood, sufficiently narrow to fit into the groove between the olecranon and the medial epicondyle, and curved to fit the contour of the elbow in a semiflexed position. These experiments also failed to produce compression tingling. Finally, the ulnar nerve was directly compressed in the arm by means of a rectangular block of wood 10 cm. long. This block was placed on the medial side of the arm, behind the medial intermuscular septum, the distal end of the block being just proximal to the medial epicondyle, and pressure was exerted forwards and inwards on the arm. Compression of the ulnar nerve in this manner regularly gave rise to compression tingling normal in onset, intensity, and duration, but restricted to the ulnar area of the hand.

In all these experiments involving compression of the ulnar nerve there was little or no interference with the peripheral circulation. This implies that the circulation to the nerve above and below the length directly pressed upon was probably normal. In all cases, however, the nerve was subjected to severe deformation. In the ruler experiments the length of nerve pressed upon was of the order of 0·5 cm. Providing that the circulation above and below this region is normal, it can readily be supposed that diffusion might take place to an appreciable extent across so small a "gap", and thus the nutrition of this small length of nerve might not be seriously interfered with. In the experiments in which the ulnar nerve was compressed above the elbow, a considerable length of nerve was pressed upon, and while diffusion might readily occur at the upper and lower ends of this region, in the centre there is probably a region in which the

processes dependent on normal circulatory nutrition are completely inhibited.

These findings, therefore, strongly suggest that the essential stimulus to the production of compression tingling is not solely mechanical deformation of the nerve, but is rather some factor connected with the inhibition of normal circulation in an adequate length of nerve, possibly acting in combination with mechanical deformation.

Returning to the cuff experiments, it has been seen that compression of a cylinder of the arm 1 cm. long by means of a tight roller bandage is capable of producing compression tingling. Such a result, at first sight somewhat at variance with the above interpretation, can be explained by the fact that in this experiment the peripheral circulation is interfered with. While diffusion into the stretch of nerve under the cuff can thus readily take place from above, little blood can enter the region from below, and in consequence a stretch of nerve " adequate " to produce compression tingling is asphyxiated. Providing that an adequate length of nerve is involved, no further increase in the length of nerve asphyxiated has any effect on the result ; it has been seen already that the results of compressing 20 cm. of nerves by overlapping cuffs are identical with these produced by a 1 cm. bandage, and by local compression of a stretch of ulnar nerve not exceeding 10 cm. in length. It has already been pointed out that compression tingling can be produced by a cuff pressure of 100 mm. Hg, but not by one of 60 mm. Hg, the length of nerve compressed being the same in both cases. When a cuff at a given pressure is applied to the arm, there is no information available to show what fraction of that pressure is transmitted directly to the nerves under the cuff. It is reasonable to suppose, however, that with a cuff pressure of 60 mm. Hg the direct pressure on the nerves is insufficient to obstruct the normal circulatory requirements of the nerve to such an extent that compression tingling is aroused, whereas a pressure of 100 mm. Hg is just sufficient to do so.

It still remains to consider whether the impulses are aroused by direct stimulation of the nerve fibres under the cuff, or whether they are due to a lowering of the threshold to stimulation in the stretch of nerve under the cuff. Lehmann (1937), using a gassing chamber technique, found that, when the phrenic and peroneal nerves of the cat are asphyxiated with nitrogen, the threshold rapidly falls and remains low until about the sixth minute ; during the period of lowered threshold, spontaneous firing occurs, which is marked about 5 minutes after asphyxia. The duration of the lowered threshold and the time of maximal spontaneous firing accord reasonably well with the time factors in compression tingling in the human arm. Heinbecker (1929), by asphyxiating frog nerves, found that the threshold to stimulation is at first lowered, and if asphyxia is prolonged, subsequently rises. Thompson and Kimball (1936), using the intact human arm, obtained results closely paralleling those of Heinbecker, though the period of asphyxia was less prolonged. In their experiments ischæmia was produced by sphygmomanometer cuffs above the elbow, a pressure of 160 mm. Hg being maintained for 16 minutes. Electrical stimulation of the main nerves at the wrist showed a rapid and progressive lowering of the threshold for about the first 12 minutes. In 5 subjects the drop in threshold progressed throughout, but in 8 cases there was a terminal rise to values equalling or exceeding the initial figure.

It thus appears that compression of the arm by means of a sphygmomanometer cuff can produce a lowering of threshold in the main nerves of the human arm, and that this result is brought about by asphyxia of the nerve trunks. At first sight, therefore, it would appear reasonable to attribute compression tingling to the presence of a lowered threshold in the nerves under the cuff. But there are two facts which render this interpretation unlikely. If the tingling is due to a lowered threshold, it would be expected that external stimuli, such as tapping or rubbing the fingers, by feeding a stream of normal impulses into the affected segment of nerve, would intensify the sensation by originating additional impulses in the affected segment. We have found that nothing of this sort occurs. Secondly, in the experiments of Thompson and Kimball, the threshold of the radial nerve was apparently as much depressed as those of the ulnar and median nerves, and, in fact, these authors illustrate the marked depression which they report by a protocol of an experiment on the radial nerve. If tingling is due merely to a drop in the threshold, therefore, there appears to be no reason why it should not occur as much in the radial nerve distribution as in the distribution of the ulnar and median nerves. This, we have already stated, is not the case.

NATURE OF THE IMPULSES.—It has been seen already that compression tingling is interpreted subjectively as touch rather than pain. In order to investigate the inference that compression tingling is the result of stimulation of touch rather than pain fibres, a subject in whom there was complete loss of pain sensibility in one upper limb was examined. The history and clinical examination of this subject may be summarized as follows.

Subject 5.—A spinal cord injury on December 7, 1945, resulted in paresis of both legs and the right arm with extensor plantar response. There was hemianaesthesia above the umbilicus on the right side. Gradual recovery of motor function took place, and left upper thoracic sympathetic ramisectomy was performed on January 3, 1946. On examination on May 30, 1946,

there was found to be loss of pain and temperature sensibility over the whole of the right upper limb and right side of the chest. Touch and vibration were completely unimpaired. Light and deep pinpricks were felt as touch ; deep pressure pain was not appreciated apart from sensation of pressure. Deep reflexes were absent in the right arm, and were increased in the right leg. Plantar reflexes were indefinite. On the left side good functional result was obtained from sympathectomy. The patient was an excellent witness.

Numerous investigations on this man at intervals over a period of 2 months showed that compression tingling could be produced in both arms by a pressure of 150 mm. Hg. On the left (sympathectomized) side, tingling began on the average 55 seconds after compression, and lasted 8½ minutes. It was felt all over the hand, and occasionally sharp pricking elements were appreciated. In the right (pain-deficient) hand, compression tingling began on the average 65 seconds after compression and lasted 8 minutes. The distribution was similar on both sides, and the only difference lay in the quality of the sensations. No sharp elements were felt on the right side, and the sensation was described as being " dead " rather than " bright " and " as though a feather were rubbing his fingers ". The findings in this subject strongly suggest that no more than a small fraction of the impulses concerned in the subjective sensation of compression tingling can be mediated by pain fibres, and that the major part of the sensation is due to impulses originating in the touch fibres. Similar results have been obtained in 3 more subjects in whom there was partial or complete loss of pain sensibility in one upper limb without any considerable interference with touch sensibility.

Discussion

It is curious that Lewis *et al.* (1931) make no mention of the occurrence of tingling arising during compression of the arm. Bourguignon and Laugier (1923) note the occurrence of tingling in such circumstances, and Bazett and McGlone (1931) refer to " intense " tingling sensations produced during compression when the periphery of the limb is maintained at a temperature of 39°C. The observations made by these authors were incidental to an investigation on temperature sensibility, but, on the basis of the difference in the tingling sensation which they state occurs with variation in the temperature of the periphery of the limb, they conclude that a peripheral chemical factor is responsible. We have been unable to detect any difference in the sensation of compression tingling with variations in peripheral temperature, and on other grounds, as has been seen, are unable to accept the hypothesis of Bazett and McGlone. Reid (1931) fails to mention the occurrence of tingling during compression, and attributes the greater part of the various sensations noted by other authors during compression to " the excess of armlet pressure on nerves". We have, however, found compression tingling to be a constant feature of any compression carried out above the elbow in normal subjects, if the pressure employed is over 100 mm. Hg.

On the evidence detailed in this paper, certain suggestions as to the nature of this tingling may be put forward :

(1) it is due to local stimulation of certain fibres of the main nerves under the compression cuff ;

(2) this stimulation is probably brought about by asphyxia rather than deformation ;

(3) the sensation produced probably originates in the main nerve trunks under the cuff, and is chiefly due to impulses arising in the fibres normally conveying the sense of touch.

Two points merit further discussion. The gradual disappearance of compression tingling in successive compressions is difficult to explain except on the basis of some form of adaptation taking place in the tissues under the cuff. Such adaptation might occur in the nerve fibres themselves, the number of fibres responding becoming less and less. If, however, the essential stimulus is asphyxia, then an adaptation of the circulatory conditions under the cuff would have precisely the same effect, the degree of asphyxia to which the nerves are subjected becoming progressively less and less. This hypothesis will be further discussed in the consideration of the mechanism of production of release pricking. It is interesting that in only one subject has compression tingling been elicited, even occasionally, by any compression distal to the elbow. In this subject the forearm contained considerable amounts of fatty tissue, and it is possible that this circumstance leads to a more even distribution of pressure within the limb, and thus to a more effective compression of the nerves. In any case, it appears that, while a cuff round the arm is effective in compressing the tissues under it, cuffs on the forearm or wrist are relatively less effective. This point will also be considered further in connexion with release pricking.

Observations on Release Pricking

Effect of Site of Compression.—Release pricking can be elicited after compression of any part of the limb, provided the pressure has been maintained for long enough. There are, however, marked differences in the results according to the site of the compression. A 16-minute compression of the arm above the elbow gives rise to severe release pricking coming on approximately 45 seconds after release,

and lasting for approximately 9 minutes, the pricking at its height extending proximally to about an inch above the level of the wrist joint. A similar compression just above the wrist produces pricking lasting about 7 minutes, coming on about 1 minute after release, greatly reduced in intensity, and usually not extending proximally further than the middle of the palm. Compression just below the elbow gives an intermediate result in duration, intensity, and distribution. Experiments in which a rubber band 1 cm. wide is tied tightly round the base of the middle finger show that a 16-minute compression at this level is completely ineffective, but that compression for 25 minutes gives a faint release pricking in the finger lasting for about 8 minutes. These results are in general agreement with those of Lewis *et al.*, except that in their paper they state that in order to produce " tingling " on release, compressions at the wrist must usually last 20 minutes or longer, and compressions of the fingers must usually last 40 minutes or longer.

Effect of Duration of Compression.—Compression of the arm above the elbow by a cuff at 150 mm. Hg for 6½ minutes is not followed by release pricking. Compressions of 7 minutes or longer at this site give rise to definite pricking, the intensity, duration, and distribution of the sensation experienced varying directly with the length of the compression. After a 7-minute compression the pricking is faint, comes on about 1½ minutes after release, is limited to the palmar surfaces of the fingers, and lasts less than 2 minutes. After a 16-minute compression, as already stated, pricking is very strongly experienced, comes on about 45 seconds after release, extends up to the wrist, and lasts approximately 9 minutes. After compressions of intermediate duration intermediate results are obtained.

It has already been stated that even from the beginning of release pricking a faint tingling sensation can be detected " in between " the pricks. As the duration of compression is increased from 10 to 16 minutes, however, other sensations begin to obtrude on consciousness. The first of these is a condition described by Lewis *et al.* as " pseudo cramp", in which the muscles of the hand feel as though they were contracted and paralysed. There is no real paralysis, but a considerable mental effort is required to move the fingers. As long as the hand is kept perfectly still during this phase there is no sensation additional to the pricking and tingling previously described. Movements of the hand or fingers while " pseudo-cramp " is present not only greatly intensify the pricking, but produce a third type of sensation. This consists of a pronounced fine vibratory " buzzing " felt locally in the fingers either on movement or on stimulation by tapping. It is noteworthy that movement or tapping intensifies the release pricking both locally and also over the whole area in which pricking is felt, the intensification lasting for some seconds after stimulation has ceased. In contrast, the " buzzing " sensation described above is never spontaneous, lasts only for the time stimulation by movement or tapping is applied, and is felt locally, i.e. only in the parts actually moved or tapped. These two additional sensations, " pseudo-cramp " and " buzzing " occur only in the first stages of release pricking, and rapidly disappear in the course of one or two minutes. Following a 16-minute compression of the arm by means of a pressure cuff it is often very difficult to separate the elements of the sensation complex presented to consciousness, but it will be seen later that, by employing other means, " pseudo-cramp " and " buzzing " may be produced together, without the complicating factors of release pricking and its underlying tingling sensation. Once analysis of the " pseudo-cramp " and " buzzing " has been made under these circumstances, it is easy to detect them following a 16-minute compression in the majority of subjects. It should be noted, however, that in some subjects a 16-minute compression is insufficient to produce these sensations, which, however, occur if compression is continued for long enough.

All these observations closely confirm the findings of Lewis *et al.*, except that these authors do not appear to have detected the additional " buzzing " element occurring on stimulation after prolonged compression.

Distribution of Sensation.—We have also confirmed the findings of Lewis *et al.* that release pricking invariably begins in the finger-tips and is most intense in the palmar aspect of the fingers and in the palm. Usually, pricking in the dorsum is slight, and after the shorter compressions it may be absent. As has been pointed out, the proximal boundary of the area in which pricking is felt is dependent on the site and duration of compression, and this boundary advances up the limb as a horizontal level, rather than in a manner corresponding to the distribution of the cutaneous nerves supplying the hand. We have not seen a case in which the distribution of release pricking is restricted to the territory of any one nerve, as occasionally happens with compression tingling. It is quite common, however, for pricking to be more intensely felt on the radial side of the hand than on the ulnar ; the reverse only infrequently occurs. It is also common for pricking to begin on one side of the hand an appreciable time before it starts on the other, and the disappearance of the sensation may obey a similar or the reverse sequence.

EFFECT OF MODIFICATION OF LOCAL CONDITIONS.—By varying the pressure in the sphygmomanometer cuff we have found that a pressure of 60 mm. Hg will not give rise to release pricking, even when compression is applied for 16 minutes. On the other hand, a pressure of 100 mm. Hg applied for 10 minutes is regularly followed by release pricking of normal quality, distribution, and duration, though of slightly reduced intensity. The full "normal" response is obtained with a cuff pressure of 150 mm. Hg, and no further increase of pressure, up to a limit of 300 mm. Hg, affects the resultant pricking. Release pricking, slightly reduced in intensity and duration, follows a 10-minute compression of the arm by a bandage 2 cm. wide applied at a tension just sufficient to obliterate the radial pulse. If the release pricking following compression by a cuff 12 cm. wide is taken as the "normal" result, then it is found that an increase beyond this figure in the length of the limb directly compressed appears to have little influence on the pricking. Thus, if two cuffs, one above the elbow and the other below, are so arranged as to overlap, and both are then inflated for 16 minutes, the result produced is indistinguishable from that produced by a 10-minute compression of the arm above the elbow by one cuff alone.

Lewis, Pickering, and Rothschild state that tingling "is of similar intensity and duration when the cuff has been applied at 150 or 300 mm. Hg, and over 12 or 24 cm. of nerve", but later they state that "the actual length of nerve released matters. . . . If a cuff 12 cm. wide is distended for 10 minutes and a second cuff of the same width is distended directly below it, and the upper cuff is now released, blood supply is restored to the nerves for a stretch of 12 cm. This gives tingling. Similarly, by overlapping two cuffs, 6 cm. of upper arm with contained nerves can be released; tingling in this instance, though quite definite, is very slight and transient."

It is not quite clear what is meant by these statements, as at first sight they appear mutually exclusive. We have taken them to mean that the authors consider that "the actual length of nerve released matters" only up to a length of 12 cm. and that no further increase in the length of the nerve compressed has any effect in increasing release pricking.

EFFECT OF MODIFICATION OF PERIPHERAL CONDITIONS.—I.—If two cuffs, one above the elbow and the other below, are so arranged as to overlap, both may be inflated together to 150 mm. Hg. If now the upper cuff be released after 10 minutes, the pressure in the lower cuff being maintained for a further 6 minutes after this time, it is found that two periods of characteristic release pricking are obtained. The first appears approximately 1 minute after release of the upper cuff, lasts for about 4 minutes, and is of very low intensity. It can hardly be doubted that this first period of pricking is to be attributed in some way to the release of the upper cuff, and at first sight it might be assumed that it is due to a return to a normal condition of the tissues under the upper cuff, the lower cuff preventing such a return to normality of the tissues peripheral to the upper cuff. Comparison of the pricking thus produced with that occurring after the release of a 10-minute compression by one cuff at 150 mm. Hg on the arm above the elbow shows that the pricking is slightly reduced in duration and distribution, and very markedly reduced in intensity. The second period of release pricking follows the release of the cuff on the forearm, 16 minutes after the start of compression, and is almost identical in intensity, distribution, and duration with the release pricking which normally follows release of a 16-minute compression of the forearm alone.

II.—If this experiment be repeated, the lower cuff this time being arranged just above the wrist, the results are slightly different. Two periods of pricking are again obtained but this time the first period is almost the same, in intensity, distribution, and duration, as the pricking produced by the release of a 10-minute compression of the arm above the elbow in the absence of a peripheral cuff. The second period of pricking in this experiment, occurring after release of the lower cuff, is less than the first, and in intensity, distribution, and duration resembles the effect normally following the release of a 16-minute compression of the wrist. Lewis *et al.* state that tingling "is felt just as strongly in fingers to which the return of blood is prevented by rubber straps tied around their bases, and almost, if not quite as strongly when the return of blood to the whole hand is prevented." With this observation we are in agreement, provided only that the cuff preventing return of blood to the hand is situated at the wrist and not just below the elbow.

III.—A variant of experiment I provides further information. A cuff was applied to the arm above the elbow for 10 minutes and then released. Half a minute before release of this cuff, another one was inflated on the forearm just below the elbow, and this peripheral cuff remained inflated for a further 6 minutes after release of the proximal cuff. This experiment produced results for practical purposes indistinguishable from the results of experiment I. A feeble period of pricking followed the release of the proximal cuff, and a severe pricking followed the release of the distal cuff. Now in this case the distal cuff was inflated for a total time of 6½ minutes, and a compression of this duration below (or indeed above) the elbow normally produces no effect whatever by itself. Yet the pricking following its release was indistinguishable from that produced by a 16-minute compression of the forearm.

IV.—Repetition of experiment III with the lower cuff at the wrist, as in experiment II, provides results indistinguishable from those of experiment II. If it is assumed that the pricking is due to the return of normal conditions to the tissues in which the impulses giving rise to pricking are initiated, then the observations on the first period of release pricking in these four experiments are capable of the following interpretation.

In an experiment with one cuff on the arm, blood returns to the whole limb peripheral to the upper margin of the cuff, giving what may be termed the

" normal " response. In experiments I and III, on release of the upper cuff, blood returns to a cylinder of tissue 12 cm. in length, giving a greatly reduced and feeble response. It is at once apparent that return of circulation to the tissues directly under the cuff is not the only factor in the production of release pricking. In experiments II and IV release of the upper cuff leads to the return of blood to a cylinder of the limb approximately 25 cm. in length (the distance from the upper margin of the upper cuff to the upper margin of the lower cuff). This produces a result almost indistinguishable from the normal response. It might, therefore, be argued that the normal response is produced by the return of blood to the tissues under the cuff plus the tissues between the cuff and the wrist. This argument leads to the conclusion that it is the length of limb to which blood returns which is the operative factor in producing release pricking. It is supported by the observed facts that, as the site of compression is moved distally on the limb, the resultant release pricking is progressively diminished. This appears to be the conclusion reached by Lewis *et al.*, though we cannot agree with them when they state that " the portion of the nerve trunk . . . lying within the cuff is chiefly responsible for subsequent tingling."

But the second period of release pricking in these experiments also requires an explanation. If, in accordance with the above hypothesis, we assume that the first period of pricking is due to the return of blood to the tissues as far as the proximal margin of the distal cuff, then this effect is exhausted before the distal cuff is released, since the pricking has disappeared by this time. It therefore follows that the second period of pricking must be due to the return of blood to the tissues under, and peripheral to, the distal cuff. In other words, the second period of pricking must be due to factors connected only with the distal cuff, such as duration and site of compression. It has already been seen that normally a 6½-minute compression of the forearm just below the elbow produces no release pricking whatever. But in experiment III release of a 6½-minute compression at this site gives rise to release pricking similar in all respects to that produced by a 16-minute compression. We are therefore forcefully driven to conclude that the presence of a cuff above the elbow for 10 minutes of the total compression time has completely altered the response following the release of the lower cuff.

It is extremely difficult to interpret this finding on any variant of the above hypothesis. It might be argued that the compression of the arm by the upper cuff induces a hyperexcitability of the nerve under it, which lasts for some time after pricking has subsided and allows impulses reaching that segment from below to be multiplied. But if hyperexcitability of the nerve trunk is called in to explain the results of experiments III and IV we must then assume that the same factor does not operate in experiments I and II, where there is no " enhancement " of the second period of pricking. Since in all four experiments the duration of the arm compression and the interval between the release of the upper and lower cuffs are the same, such an assumption is manifestly untenable. In the absence of some such phenomenon there appears to be no reason why the pricking following the release of the lower cuff in experiments III and IV should differ in any way from the pricking normally produced by a compression of similar duration at the same sites. It is, therefore, already clear that the hypothesis of Lewis *et al.* is unsatisfactory, and that an alternative one is necessary.

The only common factor between experiment I, experiment III, and a normal 16-minute compression of the forearm just below the elbow, is that in all three the circulation in the tissues distal to the elbow was impeded for 16 minutes. Yet the results ensuing after final release of compression of the forearm just below the elbow are in all three experiments essentially similar. It may, therefore, be inferred that events taking place in the periphery of the limb play a leading part in the production of release pricking.

V.—A further experiment of the same nature was also carried out. Two cuffs were applied, one above and the other below the elbow, as in experiment I, and inflated together. After 10 minutes' compression the lower cuff was released, pressure in the upper cuff being maintained for a further 6 minutes. The procedure was thus exactly the reverse of that in experiment I.

The results showed that no release pricking followed the release of the distal cuff, and that the release pricking following release of the proximal cuff was equivalent to that produced by a normal 16-minute compression above the elbow. In other words, the presence of the distal cuff produced no effect, either on its release, or on the release of the proximal cuff. Now in this experiment release of the distal cuff removed the direct pressure on a 12 cm. cylinder of forearm, but did not alter the condition of the circulation in the tissues peripheral to the proximal cuff. If the stimulus to release pricking is the removal of direct mechanical pressure on the limb, then a period of pricking would be expected following the release of the distal cuff. The fact that no such pricking occurred indicates that the stimulus is probably not of this nature. It is possible that the presence of the proximal cuff, by depressing conduction in the nerves, prevented the impulses arising after release of the distal cuff from reaching consciousness. The results are, however, consonant with the supposition that release pricking is largely occasioned by a mechanism having its origin in the tissues peripheral to the site of compression, and initiated by the return of normal circulatory conditions to these tissues.

VI.—If experiment V be repeated in the manner of experiment III—i.e. by applying the lower cuff for 10 minutes, and half a minute before its release inflating the upper cuff for a total time of 6½ minutes—again no pricking follows the release of the lower cuff. On release of the upper cuff, however, severe pricking is produced. This response is more marked than that following a 16-minute compression below the elbow, but rather less than that following a 16-minute compression of the arm above the elbow. Here again, a 6½-minute compression is normally totally ineffective in producing release pricking and it appears that events taking place in the forearm and hand due to the inflation of the lower cuff for 10 minutes have completely altered the normal 6½-minute response above the elbow.

In this case it is not so acceptable to say that the presence of the upper cuff has obstructed the passage of peripherally arising impulses, since by the time any pricking occasioned by the release of the lower cuff would be expected—i.e. about 1 minute after release—the proximal cuff has only been inflated for 1½ minutes, and it is difficult to believe h at depression of conduction in the nerves, to the extent of suppressing a vigorous sensation such as release pricking, could occur in this short time. It appears unlikely, therefore, that the essential stimulus to release pricking is the removal of direct pressure, and the evidence again favours the importance of events taking place in the periphery during compression.

Effect of Repeated Compressions.—The effect on compression tingling of carrying out repeated compressions at the same site has already been described. These experiments also yielded information on the behaviour of release pricking. The type of result obtained may be indicated by means of an example. Ten-minute compressions at 150 mm. Hg on the arm above the elbow were made in series on the same subject, the cycle interval (interval between releases) being 20 minutes. The result of the first compression was a "normal" period of pricking, felt all over the hand to the level of the wrist and lasting 6½ minutes. The second compression gave a similar result, but, after the third compression, pricking, though of normal duration, was considered to be reduced in intensity and was not felt proximal to the level of the outstretched thumb. After the fourth and fifth compressions pricking was restricted to the area distal to the metacarpo-phalangeal joints, and the sharp pricking elements in the sensation were greatly reduced. Release pricking following the fifth compression lasted 4½ minutes. After the sixth and seventh compressions the sensation was one of pure tingling, rather like a faint compression tingling, and was not felt above the proximal interphalangeal joints. After the eighth and succeeding compressions tingling did not appear spontaneously, but could be elicited, in the tips of the fingers only, by tapping. The intensity and duration of this tingling produced on stimulation gradually "faded," until after the twelfth compression no abnormal sensation of any kind could be elicited. In all these compressions the time of onset of the sensation, whether pricking or tingling, and whether spontaneous or only elicited by tapping, remained remarkably constant. Very similar results were obtained with other subjects at the same cycle interval. It may, therefore, be said that, if the cycle interval is short, release pricking becomes progressively reduced in intensity, distribution, and duration, until eventually it disappears altogether. As the cycle interval is progressively lengthened, this process takes place more and more slowly with successive compressions, until with a cycle interval of 60 minutes there is little change perceptible in the release pricking even after 13 successive compressions. Because of this phenomenon, compressions were not repeated on the same arm in the investigation of release pricking, unless an interval of 1 hour had elapsed since the last compression.

Site of Origin of the Impulses.—Just as in the case of compression tingling, it must be assumed that the impulses of release pricking take origin in the nervous tissues of the limb peripheral to the upper margin of the stretch of limb compressed. There are, therefore, the same four possibilities to be considered: (a) that the impulses arise at the peripheral nerve endings; (b) that they arise in the main nerves peripheral to the compression cuff; (c) that they arise in the nerves directly pressed on by the cuff; or (d) in a combination of the above sites.

It has already been seen that modification of conditions in the periphery of the limb during compression can exercise a profound effect upon the resulting release pricking. There is thus considerable support for the view that the impulses of release pricking take origin in the periphery, and not, as Lewis *et al.* suggested, under the cuff. Two relevant facts may be re-emphasized here. The first is that release pricking is never confined to the territory of any one nerve. Secondly, in a fully established response, pricking is always most pronounced in the pads of the digits, while it is less so in the more proximal parts of the palmar aspect of the digits and in the palm, and is faint in the dorsum of the hand and digits. In other words, the intensity of the sensation experienced is distributed in a manner roughly corresponding to the density of the peripheral innervation of the hand. Both these facts can readily be explained if it is assumed that release pricking is due to stimulation of a proportion of nerve endings in the periphery. A further point in connexion with the distribution of the sensation is also important. It has been seen that if conditions are such that pricking of minimal

distribution is produced it will occur in the finger-tips. As conditions are altered so that pricking is felt over an increased area, the upper margin of that area advances up the limb as a more or less horizontal line. This observation makes it exceedingly difficult to attribute the sensation to factors affecting the fibres of a main nerve trunk in any situation in the limb, since such a hypothesis would imply a selective action on individual nerve fibres on a distributional basis. Lewis *et al.* appear to have accepted this unlikely view, for they state : " Just as sensory loss occurs through involvement in the upper arm of the nerve fibres to the finger-tips, so tingling of the corresponding parts is similarly brought about." There is, however, no sound physiological basis for such a hypothesis, and the findings can be much more plausibly explained if it is accepted that the impulses originate at or near the peripheral nerve endings.

The effects ensuing after direct compression of various peripheral nerves were investigated by the same means as already described under compression tingling. In the first series of experiments pressure was maintained on the ulnar nerve by leaning the elbow on a round ruler placed between the medial epicondyle and the olecranon. Pressure was maintained in several subjects for varying periods up to the point where complete paralysis of all muscles supplied by the ulnar nerve in the hand had occurred. By this time there was considerable impairment of light touch sensibility over the whole of the ulnar cutaneous distribution. Release of pressure at any time up to this point was not, however, followed by any suggestion of release pricking. In all cases complete recovery of the motor paralysis and sensory loss occurred within two minutes of release, motor recovery occurring first and being apparently complete in less than one minute. During or after this recovery phase no spontaneous sensations occurred in the hand except that on two occasions a mild sensation of warmth was noted. Rather larger stretches of the ulnar nerve were then subjected to pressure at the same site by using a thin block of wood shaped to the curvature of the elbow, as described under compression tingling. Owing to the difficulty of knowing what length of nerve was pressed upon in different subjects and what pressures were actually exerted upon the nerve, there was naturally considerable variation in the results with different subjects. One such experiment may, however, be quoted as typical.

Twenty-three minutes after the institution of compression " velvety numbness " first became evident in the ulnar area. Eight minutes later this sensation had spread to involve the whole ulnar area, and was very marked on stimulation, though not spontaneous. At this time, also, hypoæsthesia had appeared in the fifth digit. Thirty-five minutes after the start of compression the interossei were partially paralysed, and the tip of the fifth finger was anæsthetic to stimulation by a number 4 nylon suture. "Velvety numbness" became spontaneous in the ulnar area one minute later. On release, 40 minutes after the start of compression, the whole of the fifth finger was anaesthetic to touch, and position sense in this digit was extremely poor. The interossei and hypothenar muscles were completely paralysed, and the ulnar half of flexor digitorum profundus was very weak. Thirty seconds after release the "velvety numbness" had completely disappeared, and thirty-five seconds after this the paralysis had gone, to be succeeded almost immediately by marked pseudo-cramp, which was accompanied by the " buzzing " sensation previously referred to as occurring after prolonged compressions of the arm by means of a sphygmomanometer cuff. Both sensations were strictly localized, the cramp to the muscles supplied by the ulnar nerve, and the " buzzing " to the ulnar cutaneous area. It must be emphasized that no spontaneous sensation occurred, the " buzzing " being felt only during the time of stimulation and only in the areas stimulated, just as the " cramp " only became evident on attempting to exercise the muscles concerned. Owing to the evanescent character of the " buzzing " it is difficult to describe its quality accurately, but it might be said to resemble an accumulation of very minute " pricking touch " impulses, much harsher and more violent than the tingling normally accompanying release pricking. Five minutes after release of compression, sensation in the hand had returned to normal. At no time was there any suggestion of release pricking or spontaneous tingling in the hand.

This buzzing sensation, elicited only by stimulation which causes neither irradiation nor after-discharge of the sensation, which does not spread centripetally up the limb, and which differs markedly in quality from the sharp bright pricks of release pricking, must be accepted as a totally different sensation. Nevertheless, it appears to have misled Lewis *et al.*, for these authors, as a result of experiments in which the ulnar nerve was compressed at the elbow by leaning it on a narrow inflatable bag, state that " tingling of precisely the same quality " (as in compression cuff experiments) " occurs in the ulnar region of the hand after release of pressure confined to the ulnar nerve at the elbow. . . . " This misinterpretation of the sensations produced in such circumstances appears to have been chiefly responsible for their conclusion that release pricking arises mainly in the nerves locally pressed upon. We are, however, satisfied that the " buzzing " sensation is not the same as release pricking, and in fact bears only an incidental temporal relationship to it. It has been shown, in these experiments, that " buzzing " may be produced without any accompanying release pricking, and it has also been seen that, following compression of less than 16 minutes' duration by means of a sphygmomanometer cuff, release pricking is regularly produced without any accompanying " buzzing " or " pseudo-cramp ". On the other hand, following compressions of 16

minutes or longer, all three sensations often appear together. We consider that the available evidence indicates that both " pseudo-cramp " and " buzzing" are due to a disturbance of the threshold in the nerves at the site of compression, occasioned by the return of normal circulatory conditions to a stretch of nerve previously deprived of blood supply, provided that an adequate length of nerve has been so affected. This explanation, while irrelevant to a discussion on the site of origin of release pricking, is inserted here to emphasize the fact that not only are the " buzzing " and release pricking completely different sensations, but the impulses subserving them arise in different sites, and, as will be seen later, are probably due to different mechanisms.

These observations on compression of the ulnar nerve were supplemented by experiments in which the lateral popliteal nerve was compressed against the neck of the fibula by crossing the knees as previously described. The findings were in complete agreement with those of the second group of ulnar experiments. After some time, " velvety numbness " appeared in the lateral popliteal distribution, to be succeeded by paralysis of the extensors and loss of light touch sensibility in the area supplied by the nerve. On release of compression at this stage, motor and sensory recovery rapidly followed, to be succeeded by " pseudo-cramp " and " buzzing ", which in turn gradually disappeared without any suggestion of pricking or, indeed, any spontaneous sensation occurring. It may be noted in parenthesis that this sequence of events, so common in everyday life, is invariably described as " pins and needles " though, in fact, no sharp pricking elements are present. An interesting and important fact, which will be referred to later, is that in these experiments, though no pricking developed in the limb in which the lateral popliteal nerve was compressed, frequently faint but typical release pricking occurred in the opposite foot on uncrossing the legs. Further experiments in which the sciatic nerve was compressed in the thigh by sitting on a round ruler gave results similar in general character to those of the lateral popliteal experiments. Finally, the median nerve was compressed in two subjects by allowing the forearm and hand to hang down vertically over the back of a wooden chair, the arm being at right angles to the trunk and to the forearm. Pressure was thus brought to bear on the nerve immediately above the bend of the elbow, and it should be noted that this procedure also obliterated the radial pulse. As the experiment proceeded, the forearm and hand became slightly cyanosed, but not congested or painful. In one subject marked " buzzing " and " pseudo-cramp ", confined to the median distribution, followed release of pressure, but in the other these sensations were also felt in the radial distribution, presumably owing to involvement of the radial nerve at the elbow. In neither subject did repeated experiments give rise to any release pricking, but in both a very faint spontaneous tingling sensation was present for the first two or three minutes after release. It will be noted that in all the other experiments in which nerve trunks were directly compressed there was no interference with the peripheral circulation, and no spontaneous sensations occurred. In the median nerve experiments, however, a spontaneous tingling did occur, and this is to be associated with some obstruction to the peripheral circulation. This point will be referred to later in the consideration of the mechanism of production of release pricking.

The above observations may be summarized by saying that direct compression of several peripheral nerves in different subjects completely failed to produce any suggestion of release pricking, provided that the circulation to the periphery remained unimpaired. It must, therefore, be concluded that the impulses of release pricking do not arise in the nerves directly pressed on by the cuff. There still remains the possibility that the impulses may arise in part at the peripheral nerve endings and in part in the main nerves peripheral to the cuff, though from the indirect evidence of the distribution of the sensation it has been seen that it is unlikely that any large proportion of the impulses originate in the latter site. The conclusion that release pricking has its origin at the peripheral nerve endings was tested by compressing the arms of the same amputation cases as took part in the investigation of compression tingling (subjects 8 and 9). Both these men had amputations between the elbow and the wrist, and therefore, on release of pressure maintained for 16 minutes above the elbow, a cylinder of arm 12 cm. long, and stretches of forearm six inches and seven inches long respectively, were released from the effects of compression. In spite of this, however, no suggestion of release pricking was felt by either subject, although in both the missing hand was fully exteriorized at the time. It seems definite, therefore, that the vast majority of the impulses conveying the sensation of release pricking are due to stimulation of the peripheral nerve endings.

MECHANISM OF PRODUCTION.—The views of Lewis *et al.* on the mechanism of production of release pricking may be summarized by two quotations from their paper :

1.—" The portion of the nerve trunk chiefly responsible for sensory loss, that lying within the cuff, is chiefly responsible for subsequent tingling. The further away the section of nerve affected lies from its peripheral ending, the more readily is conduction

depressed in it, and the more does it contribute to subsequent tingling."

2.—". . . [Tingling] is caused by a condition developed in the main nerves during their recovery from loss of blood supply."

It is plain that this explanation does not account for all the observed facts, and must, therefore, be modified or abandoned. From the evidence already presented we have been forced to conclude that the impulses of release pricking arise in or near the peripheral nerve endings. In elaborating a new theory to account for the observed facts, the starting point must, therefore, be occurrences in the periphery. We have seen that compressions of nerve trunks involving no interference with the circulation in the periphery are not followed by release pricking, whereas those in which the peripheral circulation is impeded invariably give rise to release pricking. As an intermediate case may be cited the experiments in which the median nerve was compressed at the elbow, these compressions involving a partial obstruction of the peripheral circulation by obliterating both the brachial artery and the basilic and cephalic veins. As has been pointed out, these compressions were followed by a faint spontaneous tingling sensation, which could conceivably be interpreted as a minimal response of the release pricking type.

We may therefore assume, as a working hypothesis, that the production of release pricking bears some relation to the state of the circulation in the periphery of the limb, and proceed to examine in more detail the circulatory conditions in the periphery both during and after compression of the limb by a sphygmomanometer cuff. When a compression cuff at 150 mm. Hg is placed round the limb the normal circulation to the tissues peripheral to the cuff is interrupted. That movement in the capillaries continues during compression has been shown by a few direct observations of the capillary circulation in the nail bed. We have found that, for approximately 45 seconds after applying the cuff in any site on the upper limb, circulation in the capillaries completely stops. After this time, however, a sluggish and intermittent flow starts, in a proportion varying from one sixth to one third of the capillaries in the field, and is maintained until release of compression. The capillaries open and shut down at intervals, and the direction of blood flow in the patent ones is invariably the same as that observed during normal circulation. No differences in these findings were occasioned by alteration of the site of compression, or the degree of pressure exerted. The gross effects observable in the limb during compression are, however, those of circulatory stasis. The skin assumes a leaden cyanotic colour, and measurement by means of a thermocouple show that the skin temperature falls. On release of compression, the limb flushes in reactive hyperaemia, and a considerably increased flow of oxygenated blood drives out the accumulated venous blood from the peripheral tissues. It is during this phase of reactive hyperæmia that stimulation of the peripheral nerve endings occurs, with the production of the sensation of release pricking. It is tempting, therefore, to attribute release pricking to a phenomenon consequent upon the return of oxygenated blood to the nerve endings in the periphery asphyxiated by the previous interference with their normal circulation. This implies that during the period of circulatory arrest the condition of these nerve endings has been in some way modified so that the return of normal circulatory conditions stimulates them to spontaneous firing. This must be so since hyperæmia, produced for example by heat, does not in itself give rise to any sensation resembling release pricking.

The suggestion which most readily presents itself is that this modifying factor is anoxæmia of the nerve endings. But it has already been seen that compression of the arm by a cuff at 100 mm. Hg is followed by release pricking only slightly reduced in intensity, and " normal " in all other respects. During such a compression the radial pulse continues to beat at the wrist, and the peripheral tissues must be considerably better oxygenated than when the occluding pressure is above the systolic blood pressure. If a 16-minute compression at 150 mm. Hg is carried out on the arm, and every 4 minutes the pressure is rapidly lowered to zero and immediately pumped up again, a period of three or four seconds results in which there is no obstruction to circulation in the limb. During this time four or five normal pulse beats occur, and a considerable volume of oxygenated blood is conveyed to the periphery. On final release at 16 minutes, pricking ensues which is almost indistinguishable from that following an uninterrupted 16-minute compression of the arm.

These results indicate that the implication of anoxæmia of the nerve endings as a causal factor would not afford an entirely adequate explanation. There is, however, another possibility. In a compression of the limb at 150 mm. Hg, not only is the oxygenation of the tissues interfered with by obstruction of their arterial blood supply, but the venous drainage from these tissues is also obstructed. As a result, substances, the results of normal or abnormal cell activity, tend to accumulate in the tissue spaces. The existence of one such metabolite has already been postulated by Lewis and

others in connexion with the phenomena of reactive hyperaemia (Lewis, 1927). It is interesting, therefore, to examine our results on the hypothesis that the accumulation of some substance in the tissue spaces during compression is responsible for so altering the condition of the nerve endings that they respond to removal of this substance, on release of compression, by spontaneous firing. Lewis (1927) has shown that, if a cuff pressure of 60 mm. Hg is thrown on the arm, the pressure in the main veins rapidly rises to that level, and circulation in the limb presumably proceeds almost unimpaired. It has been seen that 10-minute compressions of the arm using a pressure of 60 mm. Hg are not followed by release pricking. On the other hand, with a pressure of 100 mm. Hg there is considerable obstruction to the venous return, as evinced by swelling and congestion of the limb and the appearance of punctate hæmorrhages. At this pressure, as has already been pointed out, release pricking " normal " in all respects except intensity, is obtained after a 10-minute compression.

In the experiments quoted above, in which a 16-minute compression of the arm is released every 4 minutes, with each successive recompression the limb becomes more swollen, congested, and painful, indicating that the time of release allowed was not sufficient for the afferent side of the circulation in the limb to become cleared. It appears, therefore, that the essential prerequisite for release pricking is not obstruction of the arterial supply to the tissues, but interference with the venous return, and the observations are consonant with the implication of a hypothetical metabolite accumulating in the tissue spaces. Turning to the observed effect of increasing the duration of compression, this may readily be explained on the basis of the above hypothesis. The longer compression is maintained, the greater will be the accumulation of the metabolite, and the greater the subsequent response, in terms both of the number of nerve endings affected and the period of spontaneous firing aroused in each individual ending. The observations made on the distribution of release pricking may also be adequately interpreted. If pricking is due to the accumulation of a metabolite in the tissue spaces consequent upon interference with circulation, it might be expected that it would occur first in the parts in which circulation is most readily depressed, i.e. the finger-tips. We have seen that this is precisely what occurs. Again, the gradual spread of the sensation in an irregular horizontal line up the limb as the duration of compression is increased can be attributed to exactly the same cause. Lastly, the differences in the intensity of the sensation experienced in the different parts of the hand may easily be considered as due partly to the differences in concentration of the metabolite in a proximo-distal direction as a result of interference with the venous return being more marked at the periphery of the limb, and partly to the varying density of peripheral innervation in the hand.

So far, therefore, the hypothesis set up is capable of explaining satisfactorily all the observed facts. But we have still to consider the effects produced by altering the site of compression. It has been seen that as the compression cuff is moved distally from the arm to the finger it becomes progressively less effective in producing release pricking, and longer and longer compressions are required before pricking can be elicited. If the accumulation of metabolites in the periphery is responsible for these effects, then it follows that these metabolites must accumulate more readily when the cuff is on the arm than when it is on the forearm, and so on down the limb. In order to explain this inference we must make a further assumption, that a cuff on the arm is more effective in impeding the circulation in the hand than one on the forearm, that a cuff on the forearm is more effective than one on the wrist, and that this in turn is more effective than one on the finger. The anatomical configuration of the limb in these four sites lends considerable support to this assumption. In the arm the main vessels, with the exception of the profunda artery, lie in exposed positions where they are vulnerable to the effects of compression. In the forearm, however, a considerable volume of blood flows up and down the limb by means of vessels placed more deeply, and partly protected from the effects of compression by lying centrally between the two bones. Again, in the finger it is probable that a considerable circulation can take place through the bone, the cross-sectional area of which is here very large in relation to the cross-section of the limb. It may also be mentioned here that accumulated surgical experience has indicated that tourniquets applied round the forearm are much less effective than those applied round the arm. Again, as a result of consideration of the mechanism of production of compression tingling it has already been suggested that compressions on the forearm are less effective in transmitting pressure to the underlying tissues than compressions on the arm. Experiments with a finger oncometer, in which the finger was maintained at a constant temperature during compressions in various situations on the limb, showed that a small increase in volume of the finger usually occurred, but there appeared to be no difference in the results according to the site of compression. These experiments are, however, necessarily misleading, since the point which is being investigated is not the mere accumulation of fluid

in the periphery, but the amount of circulation occurring in the peripheral tissues.

It may, therefore, be said that no direct evidence can be adduced here in favour of the assumption that compressions on the arm are more effective in impeding the circulation in the hand than compressions on the forearm, and so on. Very strong evidence will, however, be presented later to indicate that the hypothesis is correct. Armed with this assumption, we may proceed to interpret the results of the experiments involving modification of peripheral conditions during compression (experiments I to VI).

In experiment I, in which two cuffs were employed, one above and the other below the elbow, the upper one being released at 10 minutes and the lower one at 16 minutes, an "adequate" obstruction to the circulation in the hand was maintained for 10 minutes. At this time the "adequate" cuff was removed, leaving a less effective block to the circulation in the shape of the lower cuff. As a result, a certain amount of the hypothetical metabolite, accumulated during the previous ten minutes, was washed away from some of the peripheral nerve endings, thus stimulating them to spontaneous firing which produced the first period of release pricking. This pricking was necessarily feeble, since only a very partial recovery of circulation had taken place. After removal of the upper cuff, the circulation in the hand rapidly became adapted to its new level of depression, and at the time of release of the lower cuff the amount of metabolite accumulated in the periphery was practically the same as would have been produced by a 16-minute compression of the forearm. On completely releasing the circulation, the resulting release pricking was, therefore, indistinguishable from that produced by a 16-minute compression of the forearm.

In experiment II, where the lower cuff was at the wrist, the recovery of circulation on releasing the upper cuff was greater than in experiment I, since we have assumed that a compression at the wrist is less effective than one just below the elbow. The first period of release pricking was, therefore, much more pronounced; and, in fact, the findings show that it was only very slightly less than if no cuff at the wrist had been present. Here again, the second period of pricking was exactly comparable to that occasioned by a 16-minute compression at the wrist. Experiments III and IV may readily be explained by precisely similar reasoning. In experiment V, in which two cuffs were again used, the distal cuff this time being released before the proximal cuff, it was found that release of the distal cuff produced no effect whatever. This is to be expected, since throughout the whole 16 minutes of compression an adequate obstruction to the circulation in the hand was maintained by the cuff on the arm above the elbow.

In experiment VI the reasoning is more complicated. Here the cuff below the elbow was applied for 10 minutes, and half a minute before its release another cuff was applied on the arm and maintained there for a further six minutes after release of the distal cuff. We should expect no pricking to follow release of the lower cuff, since the circulation in the hand was still obstructed by the cuff on the arm. By the time of release of the upper cuff, 16 minutes after the beginning of the experiment, the circulation in the hand had been maintained for 9½ minutes at the level imposed by a forearm compression, but for the remainder of the time had been still further reduced by the cuff on the arm. It could, therefore, be predicted that the pricking following final release would be more marked than that following a 16-minute compression of the forearm. On the other hand the "adequate" obstruction to circulation occasioned by the cuff on the arm only lasted for 6½ minutes of the total compression time. We should, therefore, expect that the result would be not quite so marked as that following a 16-minute compression of the arm. It has been seen that these predictions are verified by the experimental findings.

The effects produced by repeated compressions at the same site remain to be explained. It has been shown that, when compressions are carried out on the arm with a short cycle interval, the pricking ensuing after each successive compression becomes progressively less and less, and ultimately disappears. Similar results are obtained by repeatedly compressing the forearm or wrist. If release pricking is the result of the accumulation of a tissue metabolite following obstruction of the blood supply to the hand, this phenomenon is susceptible of two explanations. First, it might be concluded that the activity of the cells in the periphery becomes depressed by successive periods of anoxæmia, so that progressively smaller amounts of the active substance accumulate. Secondly, and more probably, we may assume that, as a result of repeated compressions in the same site, alternative vascular channels which are not so subject to direct pressure are opened up under the cuff, with the result that successive compressions lead to less and less interference with the circulation in the hand. It follows that removal of the hypothetical metabolite from the periphery will thus become progressively easier, and the pricking following release will, therefore, become progressively less. The possibility of circulatory adaptation occurring under the cuff has already been put forward as a result of discussing

the mechanism of production of compression tingling, and further indirect evidence will be adduced later in support of this assumption.

A few experiments were done in which a series of alternate 10-minute compressions of the arm and forearm of the same limb were performed at a cycle interval of 25 minutes. The interval between releases of the arm compressions was thus 50 minutes. It was found that the release pricking following releases above the elbow " faded " in a manner characteristic of a cycle interval of 50 minutes, but that the release pricking following the forearm releases " faded " in a manner characteristic of a 25-minute cycle. For example, after the twelfth compression in one such experiment (the sixth compression of the forearm) release pricking lasted only 1 minute and was very feeble, but after the thirteenth compression (the seventh compression of the arm), release pricking was quite strongly felt and lasted 4½ minutes. If the second of the explanations put forward above to account for the results of experiments involving repeated compression is accepted, this finding may easily be explained by assuming that not only are compressions below the elbow less effective initially than those above in obstructing circulation in the hand, but circulatory adaptation takes place more rapidly in the former site. Lastly, we may refer again to the experiments in which the lateral popliteal nerve was compressed by crossing one leg over the other. It has already been stated that after the adoption of this posture for periods of the order of 40 minutes, though no release pricking was observed in the limb in which the nerve was compressed, frequently faint but unmistakable release pricking occurred in the contralateral foot in thin subjects. Now when one thigh is crossed over the other in this manner, a consideration of the anatomy of the parts shows that in the supporting thigh both the femoral artery and the long saphenous vein may be pressed upon. There is probably, therefore, a very slight but definite interference with the circulation in the foot of this side, and it is quite reasonable to suppose that, after a prolonged period of pressure, sufficient of the hypothetical metabolite would accumulate in this foot to cause a faint and short period of release pricking subsequent to the removal of the compressing limb.

We are now in a position to state that all the observations we have made on release pricking can be satisfactorily explained by postulating the accumulation of some chemical substance in the tissue spaces of the periphery during the period of compression, as a result of interference with the normal circulation. On release of pressure, this substance is washed away, leaving the peripheral nerve endings in a hyperexcitable state so that they give rise to impulses. To explain some of the findings, two additional assumptions are necessary: (*a*) that owing to the anatomy of the parts, as the site of compression is moved distally on the limb, the interference with the circulation in the hand becomes progressively less effective; (b) that, as a result of repeated compressions, circulatory adaptation takes place under the compressing cuff, this being achieved slightly more readily in the forearm than in the arm.

Neither this theory, nor the assumptions entailed in its establishment, do violence to current physiological or anatomical concepts, and direct or indirect evidence has been adduced in support of each step in its elaboration. Nevertheless, if events known, or strongly suspected, to be connected with the accumulation of metabolites in the periphery during compression could be shown to behave in a manner exactly comparable with the behaviour of release pricking, the evidence in support of the theory would be enormously strengthened. It was accordingly determined to repeat the experiments reported in this paper with a view to ascertaining the behaviour of the reactive hyperæmia occurring after release.

Experiments on Reactive Hyperæmia

The view that metabolites accumulating in the tissue spaces during circulatory arrest are responsible for reactive hyperæmia was suggested by Roy and Brown (1879), and has received powerful support from Lewis *et al.* (Lewis, 1927). The statement of Lewis (1927) that " reactive hyperæmia illustrates how vasodilation may be produced by normal metabolic substances " does not appear to have been questioned since, and, particularly as the result of the recent work of Anrep *et al.* (1944), we may accept the fact that reactive hyperæmia is due to the accumulation of a normal metabolite in the tissue spaces during the period of compression and manifesting its presence on release of compression. It is apparent that this is a mechanism precisely similar to the one we have postulated above to account for the production of release pricking. Though the metabolites responsible for the two effects are not necessarily the same, it is clear that any manipulations affecting the response produced by one would also be expected to affect the response produced by the other.

Experiments on reactive hyperæmia were carried out on two subjects, the results being photographed in colour. In all cases the other arm of the same subject was used as a control. The procedure and precautions taken were exactly similar to those previously detailed for the experiments on release pricking. In the first experiment a cuff was placed on the left wrist and another on the right arm above

the elbow. Both were then inflated for ten minutes at a pressure of 150 mm. Hg. Just before release the condition of the two hands was compared. A marked difference was at once evident, the left hand being grossly congested and of a general purple colour, but with irregular red patches, while the right hand showed no congestion and was of a general slate grey colour (Fig. 1). On release of compression reactive hyperæmia appeared in both hands but was rather slower in development in the left than the right, and at its maximum there was a pronounced difference between the two hands, hyperæmia being much more marked on the right side (Fig. 2). A similar experiment with a cuff on the forearm controlled by a cuff on the other arm above the elbow produced similar results, the reactive hyperæmia again being more marked on the side of the arm compression, though in this case the difference between the two hands was not so marked as when the lower cuff was at the wrist. It may therefore be said that, just as a cuff on the arm is more effective in producing release pricking than one on the forearm, and this in turn than one on the wrist, so a similar effect holds good for the production of reactive hyperæmia. Since the latter effect is strongly suspected to be due to the accumulation of a metabolite in the periphery, the evidence is consonant with the theory that release pricking is also due to such a mechanism.

Two cuffs were then placed on the right arm, one above and the other below the elbow, and experiment III was repeated : that is to say, the upper cuff was inflated for 10 minutes, and 30 seconds before release of this cuff the lower one was inflated, remaining so for a total time of 6½ minutes. This series of manipulations was controlled on the other limb by a cuff which remained on the forearm for 16 minutes. On release of the upper cuff on the right arm there was flushing of the right hand in spite of the presence of the second cuff on the forearm. This hyperæmia gradually " settled down " until, 15 minutes after the start of compression on both sides, there was little difference between the appearance of the two hands, both being congested and purple, with some red patches, and both exhibiting dilated superficial veins. Following the final release at 16 minutes, no difference could be detected between the hyperæmia developing in the two hands. In this experiment also, the behaviour of the reactive hyperæmia exactly parallels the behaviour of the release pricking. It is unnecessary to detail the results of repeating the other experiments in which the peripheral circulatory conditions were modified by the use of two cuffs, since in all cases the behaviour of release pricking and reactive hyperæmia was exactly similar.

Repeated compressions were carried out on the left arm above the elbow, the cycle interval being 20 minutes. The reactive hyperæmia ensuing after the ninth such compression was compared with that produced by a single compression at the same site in the control arm, and was found to be very markedly diminished in comparison (Fig. 3). Similarly, the reactive hyperæmia following on repeated alternate compressions of the arm and forearm of the same side was investigated. Thirty seconds after release, photographs were taken of the hyperæmia consequent on the sixth release (release 3 of the forearm) and the seventh release (release 4 of the arm) respectively. It was found that the hyperæmia following the seventh release was considerably greater than that following the sixth release, as was the release pricking. Lastly, it was found that reactive hyperæmia was produced after a 10-minute compression of the arm by a pressure of 100 mm. Hg, but not by a similar compression at 60 mm. Hg. Fig. 4 shows the difference in two arms so treated, 1 minute after release.

All these experiments may be summarized by saying that in every case the behaviour of reactive hyperæmia ran parallel to the behaviour of release pricking. That is, under circumstances where release pricking is marked there is also present a considerable reactive hyperæmia, and, when release pricking is only faintly experienced or absent, reactive hyperæmia is also slight or absent. Now, reactive hyperæmia has been accepted by many workers as due to the accumulation of a normal product of tissue metabolism in the tissue spaces, and these findings, therefore, strongly support the theory that release pricking is due to a similar mechanism. We therefore conclude that release pricking is the result of the removal from the tissue spaces of a metabolite, which accumulates there during a period of complete or partial circulatory arrest, and by its accumulation leads to the production of hyperexcitability of the peripheral sensory nerve endings.

Nature of the Impulses

Lewis *et al.* (1931) suggested, largely on the basis that release pricking can be " reinforced " by peripheral tactile or pressure stimulation, that the impulses are conveyed by touch fibres. " The reinforcement of tingling by peripheral tactile stimuli, the absence of reinforcement when anæsthesia of the fingers is complete but pain stimuli are still conducted, are amongst the facts tending to suggest that tingling is an affair of the tactile nerves." However, they add the following qualification: " That it is wholly produced in this way is contradicted by the fact that tingling in the fingers is felt after proximal release of 12 cm. of upper arm at a time when these fingers are quite anæsthetic."

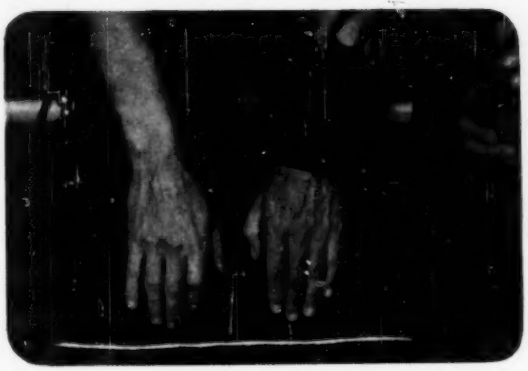

Fig. 1 (top left).—Shows the difference in the colour of the right and left hands immediately before release of simultaneous 10-minute compressions. On the right side the compression cuff is above the elbow, while on the left side it is at the wrist.

Fig. 2 (top right).—The same hands 30 seconds after release on the 10-minute compressions, showing the difference in reactive hyperæmia on the two sides.

Fig. 3 (lower left).—Reactive hyperæmia 30 seconds after release of simultaneous 10-minute compressions above the elbow. On the right side no compression had been carried out for more than 2 hours previously, but on the left side the compression was the ninth in a series of 10-minute compressions, the interval between the initiation of each compression being 20 minutes.

Fig. 4 (lower right).—This figure shows the difference in colour of the two hands 1 minute after release of simultaneous 10-minute compressions above the elbow. On the right side the pressure employed was 100 mm. Hg, while on the left side the pressure was 60 mm. Hg.

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It has already been stated that, in all the subjects so far tested by us, the sensation of release pricking was interpreted as pain rather than touch, but that there appeared to be an underlying touch component. Direct evidence on this point was obtained from the four subjects with loss of pain sensibility on one arm who afforded evidence on the same point in connexion with the nature of compression tingling. The results in all four were similar, and may be summarized by the experience of subject 5, who was an extremely accurate observer and the most clear-cut case in the group. This man, after a 10- or 16-minute compression, consistently reported a " very fine rushing sensation " in the pain-deficient hand, beginning at the appropriate time for release pricking and lasting for the normal period. This " rushing " sensation was accompanied by a feeling of " blunt pins pushing through the skin." At no time did he experience any of the coarse, sharp pricking which constitutes the major element of release pricking. The sensations which he did feel were restricted to the thenar eminence and the palmar surfaces of the index and middle fingers, occasional " tingles " being felt in the palm. These findings strongly suggest that a large proportion of the impulses in release pricking are carried by pain fibres, and tend to support the subjective interpretation of the sensation.

It has already been noted that the sympathetic supply to the " control " arm of subject 5 had been interrupted surgically six months before examination. After a 10-minute compression above the elbow in this arm he experienced sharp painful release pricking, which from his description appeared to be identical with the sensation produced in a normal arm, and was of similar distribution. (It was exactly similar to, though more marked than, the sensation produced by release of compression on the left thigh above the knee, both sensibility and vascular bed being normal in the left lower limb.) The duration of the sensation in the sympathectomized arm was, however, shorter than usual, lasting only 2¼ minutes. The sympathectomy in this man was " functioning " very well, as judged by the superficial difference in the circulation and skin temperature between the sympathectomized limb and the other arm. This result, therefore, renders it improbable that the pain sensation in release pricking is carried by the usual sympathetic channels.

We therefore conclude that the impulses in release pricking are conveyed mainly in the afferent somatic fibres normally subserving the sensation of pain, but that there is also a subsidiary element of touch in the sensation complex.

Discussion

We have found that " release pricking " is consistently felt in the hand following compression in any site on the upper limb, provided that the pressure applied is 100 mm. Hg or more and that the duration of compression is long enough. On the basis of the evidence discussed in this paper we may put forward the following conclusions :

1. " Release pricking " is due to the stimulation of a proportion of the peripheral nerve endings in the area in which it is felt.

2. This stimulation is probably occasioned by the removal, from the tissue spaces around these nerve endings, of a chemical substance which accumulates there during the period of circulatory depression.

3. The greater proportion of the impulses thus aroused are conveyed in the afferent somatic fibres normally subserving the sensation of pain.

Several authors (Bourguignon and Laugier, 1923 ; Bazett and McGlone, 1931 ; Reid, 1931 ; Lewis *et al.*, 1931) have mentioned the occurrence of " tingling " or " pins and needles " following the release of circulatory arrest in a limb. Bazett and McGlone (1931) attribute both the tingling occurring during compression and the tingling following release to a chemical factor. These authors, however, make no distinction between the two types of " tingling ", and the evidence on which they base their hypothesis consists only of the observation that both types of " tingling " are more marked when the periphery of the limb is maintained at a high temperature (39° C.). This observation, as has been noted previously, we are unable to confirm. It is perhaps curious that, if " release pricking " is due to the accumulation of a metabolite in the tissue spaces, as we assume, an increase in peripheral temperature does not affect the characteristics of the sensations. It might be argued that such an increase in temperature, by increasing the rate of chemical reactions in the tissues, would lead to the production of an increased amount of the metabolite responsible for " release pricking," and thus to an increased response. But there are many explanations which could account for the absence of any such increase, perhaps the most acceptable of which is that an increase of temperature in the periphery will also modify the circulatory conditions there. This would possibly result in an increased facility in the process of removal of the metabolite from the tissue spaces, which would counterbalance the increased production of the substance.

Bazett and McGlone also make the statement that the chemical factor which they postulate " presumably is formed more rapidly in the muscles, since stasis involving muscular regions is much more effective than stasis of the fingers, which contains

only smooth muscle." The experiments of Lewis *et al.* and our own results effectively dispose of this hypothesis. Reid (1931) notes the occurrence of " a lively sensation of pins and needles " in the hand and fingers following the readmission of blood into the forearm after ischæmias of 15 to 35 minutes' duration. In addition, he mentions the occurrence of fibrillary twitchings in the muscles of the hand and forearm in the early stage of the " pins and needles." We have frequently observed such fibrillation, and, like Reid, find it to be most common in the small muscles of the hand. Reid attributes the " pins and needles " and the fibrillation to " phases in the recovery of nerve endings and of muscle fibres respectively," but without bringing forward any evidence to support his contentions. The work of Lewis *et al.* on " release pricking " has been referred to throughout this paper, and it has already been stated that for the reasons cited in the text we are unable to accept their conclusions. It is interesting that these authors advance precisely the same theory to account both for the occurrence of " release pricking " and also for the centripetal spread of sensory loss in prolonged compressions of the limb. It has been seen that " release pricking " can be much more readily explained on the basis of a chemical mechanism acting at the periphery, and it is possible that a repetition of the work of Lewis *et al.* on sensory loss might show that these experiments also are capable of a similar interpretation.

Summary

When a human limb is compressed by means of a sphygmomanometer cuff at a pressure of 100 mm. Hg or over, a number of sensations are consistently aroused in the compressed limb, both during and after compression. Two of these sensations, which have been termed " compression tingling " and " release pricking " respectively, have been described in detail.

" Compression tingling " is a fine tingling felt in the periphery of the limb during the period of compression, and evidence has been put forward to show that it is due mainly to stimulation, by asphyxia, of some of the touch fibres in the main somatic nerves directly pressed on by the cuff.

" Release pricking " is a coarse sharp pricking sensation felt in the periphery of the limb after release of the compression cuff. It has been concluded that this sensation is conveyed mainly by somatic pain fibres, and that it is due to the stimulation of a proportion of the peripheral nerve endings in the area in which it is felt. This stimulation is probably occasioned by the removal, from the tissue spaces around the nerve endings, of a chemical substance which accumulates there during the period of circulatory depression.

The term " pins and needles ", as commonly applied in everyday life, is a loose generalization which covers a number of clearly defined subjective sensations.

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BOOK REVIEWS

AGNOSIA, APRAXIA, APHASIA. THEIR VALUE IN CEREBRAL LOCALIZATION

J. M. Nielsen

(New York. Paul B. Hoeber, Second edition. Pp. 292 ; 59 illustrations. $5.00.)

In this second edition of his book, Dr. J. M. Neilsen, Associate Clinical Professor of Medicine (Neurology) University of Southern California, presents the evidence on which he has based various published statements on the functions of speech and voluntary action, and the disturbance of these functions in disease. Thirty pages are devoted to a discussion of terminology, and the author puts forward various new terms, including "irreminiscence, visual, verbal, temporal,"—which is described as meaning "loss of ability to revisualize words due to a lesion of the temporal lobe." We are reminded of a judge who, in Court recently, asked a medical witness to speak English.

The early pages of this book give a useful outline of the subject ; the latter half will be of more use to the specialist.

THE PRINCIPLES OF NEUROLOGICAL SURGERY

Loyal Davis

(London. Henry Kimpton, 1946. Pp. 540 ; Illustrated. 37*s*. 6*d*.)

Mr. Loyal Davis's well-known text book on neurological surgery has now reached its third edition. Like its predecessors, this thoroughly revised edition gives ample evidence of the author's wide experience, reliable judgement, and literary abilities. Students should continue to find this book stimulating and readable.

SHOCK TREATMENTS AND OTHER SOMATIC PROCEDURES IN PSYCHIATRY

Lothar B. Kalinowsky and Paul H. Hoch

(London. William Heinemann Medical Books, 1946. Pp. 294. 21*s*.)

Writing on what has become an extremely controversial subject, these authors fail to make plain their own point of view, although they have been critical in evaluating their own results in the two main therapeutic methods of insulin coma and artificially induced convulsions. The book contains a number of useful facts, but the reader is left to sift what is valuable from much that is not.

MODERN ATTITUDES IN PSYCHIATRY

(The March of Time, 1945. New York : Columbia University Press. London : Oxford University Press, 1946. Pp. 154. 13*s*. 6*d*.)

The New York Academy of Medicine sponsors certain lectures for laymen. The subject for 1945 was psychiatry in medicine, and this volume contains the lectures by six distinguished American psychiatrists. The modern attitude is here set out with admirable clarity for the intelligent layman. The book shows that it is possible to present difficult medical problems in a non-technical and easily understandable form.

THE PSYCHO-ANALYTICAL TREATMENT OF CHILDREN

Anna Freud

(London. Imago Publishing Co. Ltd., 1946. Pp. 98. 10*s*. 6*d*.)

Anna Freud considers that the play technique adopted by Mrs. Melanie Klein, which is popular in this country, is too objective and leaves too much to the interpretations of the analyst. Her own technique is to establish an alliance with the child at the beginning of the treatment, and she assures the young patient that the "devil" which he recognizes inside him can be exorcized with the help of the analyst.

These lectures are presented in highly technical language, but this need not put off those who do not wholeheartedly belong to the psycho-analytical school ; they provide much material which is instructive and interesting.

THE BIOLOGY OF SCHIZOPHRENIA

R. G. Hoskins

(London. Chapman and Hall, 1946. Pp. 192. 15*s*.)

Dr. R. G. Hoskins, who is the Director of Research at the Worcester State Hospital, summarizes work on disturbances of bodily function in schizophrenia and forecasts the trend of future research. On the whole the findings are negative, and Dr. Hoskins' style tends to be involved.

PERIPHERAL NERVE INJURIES. PRINCIPLES OF DIAGNOSIS

Webb Haymaker and Barnes Woodhall

(London. W. B. Saunders Company. Pp. 227. 225 Illustrations. 22*s*. 6*d*.)

This book has been sponsored by the United States Army, and the material for it was collected in Army hospitals. The authors' main purpose has been to help Service medical officers in diagnosing peripheral nerve injuries, but the work is of greater scope than any such guide produced on this side of the Atlantic. Some of the techniques described differ slightly from those to which British workers are accustomed, but they are all useful. The clinical descriptions of nerve injuries are clear, and the illustrations excellent. This is a first-class reference book for clinicians ; though not written for the expert, it should be useful in teaching.

The following have also recently been published.

Group Psychotherapy : Theory and Practice. By J. W. Klapman. London : Wm. Heinemann. 1946. Pp. 344. 21*s*.

A historical and anthropological summary is followed by an account of group transferences and formations, group and individual psychotherapy, and the use of the psychodrama.

Traite de Neuro-Endocrinologie. By G. Roussy and M. Mosinger. Paris : Masson. 1946. Pp. 1,106. 2,200 fr.

An account of the hypothalamic-hypophyseal mechanism, and its nervous and hormonal connexions.

A Practical Handbook of Psychiatry for Students and Nurses. By L. Minski. London: Heinemann. 1946. Pp. 128. 6*s*.

An account of psychiatry with clinical descriptions and chapters on personal and occupational therapy.

The Psycho-analytic Theory of Neurosis. By Otto Fenichel. London: Kegan Paul, Trench, Truber. 1946. Pp. 703. 35*s*.

The author claims to present the psycho-analytic doctrines in a systematic and comprehensive manner. Part I includes an account of medical development, Part II that of the psycho-analytic theory of neurosis.

Les Gliomes Infiltres du Tronc Cerebral. By G. Guillain, I. Betrand, and J. Gruner. Paris: Masson. 1945. Pp. 286. 450 fr.

After a historical introduction there is an illustrated discussion on brain-stem tumours characterized by absence of raised intracranial pressure and rapid development.

The Normal Encephalogram. By L. M. Davidoff, and C. C. Dyke. London: Henry Kimpton. 1946. Pp. 232. 27*s*. 6*d*.

An illustrated account of the technique of encephalography.

Psychiatric Interviews with Children. By various contributors. Edited by Helen L. Witmer. London: Geoffrey Cumberledge. New York: The Commonwealth Fund. 1946. Pp. 443. 25*s*. 6*d*.

Records of psychiatric treatment of children in American child-guidance clinics, with comments by the editor. Intended for students and practitioners of child psychiatry.

War Stress and Neurotic Illness. By A. Kardiner and H. Spiegel. London: Paul B. Hoeber. 1947. Pp. 428. $4.50.

A monograph on war neuroses and the treatment of their acute and chronic phases.

CORRECTION

In a review of "Diseases of the Nervous System" by F. M. R. Walshe, which appeared on page 112 of the *Journal of Neurology* for July, 1946, it was said that this text-book had reached its sixth edition. The publishers, Messrs. E. and S. Livingstone, point out that the present edition, which came out in January 1947, is the fifth.